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TECHNICAL REPORT
NADC-79048-60

HIGH VOLTAGE DC STABILITY ANALYSIS MODELS

David L. Sommer
Ishaque S. Mehdi

February 1981

Final Report For Period August 1979 - October 1980

Approved For Public Release;
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Prepared For

NAVAL AIR DEVELOPMENT CENTER 60141
WARMINSTER, PENNSYLVANIA 18974

81002 40

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER NADC-79048-60	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) HVDC ELECTRICAL SYSTEM STABILITY ANALYSIS MODELS		5. TYPE OF REPORT & PERIOD COVERED FINAL August 1979 - October 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. L. Sommer I. S. Mehdi		8. CONTRACT OR GRANT NUMBER(s) N62269-79-C-0265
9. PERFORMING ORGANIZATION NAME AND ADDRESS Boeing Military Airplane Company Advanced Airplane Branch P.O. Box 3707, Seattle, WA 98124		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N62269-79-61-91132
11. CONTROLLING OFFICE NAME AND ADDRESS Advanced Electrical Systems Laboratory Naval Air Development Center Warminster, PA 18974		12. REPORT DATE October 1979
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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HVDC System Models
Electrical Systems
EASY
Mathematical Models
Dynamic Analysis
Generation Systems
Flat Conductor Feeders
Switching Regulators

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Mathematical models were developed for a variety of High Voltage DC System components which include a switching regulator, wound rotor generation system, solid rotor generation system, flat two-conductor feeder and electrical loads. The models were developed for utilization in the EASY-HVDC dynamic analysis computer program simulation.

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FOREWORD

This report presents results of work conducted by the Boeing Military Airplane Company, Seattle, Washington, under Navy Contract N62269-79-C-0265 "High Voltage DC Stability Analysis Models" during the period from August 15, 1979, to October 17, 1980. This contract was conducted under the sponsorship of the Electrical Systems Sections, Naval Air Development Center (NADC), Warminster, Pennsylvania, with Mr. Joseph Segrest as project engineer.

This report is comprised of HVDC system component mathematical model development and HVDC system model simulations using the EASY computer program. In addition to this report, a User's Manual (Reference 1) was prepared as part of a 4-day course presented to NADC personnel the week of May 19, 1980, to provide a reference for day to day usage of the HVDC system models and their application to the EASY program. This document fulfills the requirements of CDRL item number A005, Final Technical Report and CDRL item number A006, Document Data Base Design.

The program manager was I. S. Mehdi, and the principal investigator was D. L. Sommer.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
BMAC	Boeing Military Airplane Company
DCSP	Digital Control Signal Processing
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulses
HVDC	High Voltage Direct Current
IPFM	Integral Pulse Frequency Modulation
MAPPS	Modelling and Analysis of Power Processing Systems
NADC	Naval Air Development Center
PESC	Power Electronic Specialists Conference
P.O.R.	Point of Regulation
VDC	Voltage Direct Current

LIST OF SYMBOLS

A	Currents Through Conductive Elements Of The Electrical System
A_{EX}	Generator's Exciter Field Current
A_F	Generator's Main Field Current
A_{LO}	Current Through Switching Regulator Filter Inductor
A_{LO}	Current Through Generator Filter Inductor
A_L	Generator Load Current, Channel 1
A_L	Feeder Load Current, Channel 1
A_{L1}	Generator Load Current, Channel 2
A_{L1}	Feeder Load Current, Channel 2
A_{VT}	Lighting Load Inrush Current Function
A_X	Cross Sectional Area Of Flat Conductor
C	Capacitance Value For Electrical System Capacitors
C_P	Capacitance Value Of Primary Dielectric Of Flat Conductor Insulator
C_S	Capacitance Value Of Secondary Dielectric Of Flat Conductor Insulator
D_T	Differential Time For Switching Regulator Control Loop
e_c	Switching Regulator Control Error Voltage
e_i	Switching Regulator Input Voltage
e_o	Switching Regulator Output Voltage
E_C	Switching Regulator Control Error Voltage
E_I	Switching Regulator Input Voltage
E_I	EMI Filter Input Voltage
E_0	Switching Regulator Output Voltage
E_0	Permittivity Constant
E_R	Switching Regulator Reference Voltage
E_T	Switching Regulator Error Control Threshold Voltage

LIST OF SYMBOLS (CONTINUED)

FC	Flat Two-Conductor Feeder Component
F4	Switching Regulator EMI Filter Component
G	Wound Rotor Generation System Gain Constants
G1	Solid Rotor Generator/Regulator Component
i	Currents Through Conductive Elements Of The Switching Regulator
I_L	Current Through Inductive Element Of The Flat Conductor Feeder
I_2	Total Load Current Supplied By The Flat Conductor Feeder
K_D	Error Control Ratio
K	Wound Rotor Generator/Regulator Control Constants
K	Solid Rotor Generator/Regulator Control Loop Gains
LC	Filter With Inductive And Capacitive Elements
L	Electrical System Inductance Values
L6	RLC Load Component
L7	Lighting Load Component
M_F	Conversion Constant For Flat Conductor Feeder
n	Transformer Turns Ratio For Switching Regulator Feedback Control
N	Transformer Turns Ratio For Switching Regulator Feedback Control
P_D	Primary Dielectric Constant For Flat Conductor Feeder Insulation
P_{DT}	Primary Dielectric Thickness
PDR	Gain Constant For The Phase Delay Rectifiers Of The Solid Rotor Generation System
Q	Control Switch Position Of The Switching Regulator
R	Electrical System Resistor Resistance Values
R_A	Electrical Series Resistance Associated With Capacitors
RLC	Load Component With Resistive, Inductive And Capacitive Elements
R_0	Inductor Series Resistance

LIST OF SYMBOLS (CONTINUED)

S_D	Secondary Dielectric Constant For Flat Conductor Insulator
S_{DT}	Secondary Dielectric Thickness
S_F	Flat Conductor Conversion Constant
S4	Switching Regulator Component
T	Time
T_D	Differential Time For Switching Regulator Control Loop
T_R	Minimum Switching Regulator Switch Off Time
TS	Minimum Switching Regulator Switch On Time
V	Electrical System Model Voltages
V_{EX}	Wound Rotor Generator Exciter Voltage
V_F	Wound Rotor Generator Main Field Voltage
V_{IN}	Input Voltage To The Flat Conductor Feeder
V_{LX}	Wound Rotor Generator's Exciter Feedback Voltage
V_P	Rectified Voltage Out Of The Phase Delay Rectifier
V_R	Solid Rotor Generator/Regulator Reference Voltage
V_0	Solid Rotor Generator/Regulator Output Voltage
V_1	Load Input Voltage
W	Wound Rotor Generator Machine Speed
W_L	Flat Conductor Length
W_T	Flat Conductor Thickness
W_W	Flat Conductor Width
W_4	Wound Rotor Generation System Component
X	System Intermediate State Variable
Z	Switching Regulator Control Loop Constant

SECTION I

INTRODUCTION AND SUMMARY

1.1 Background

The Naval Air Development Center, NADC, has been involved in developing High Voltage DC, (HVDC) electrical systems and developing analytical techniques and procedures for predicting dynamic behavior for these systems.

The development of advanced avionics systems has increased the demands for generation, distribution, and utilization of electrical power. Highly reliable, good quality power is to be provided for the critical mission and flight essential systems for aircraft of the 1985 and beyond time periods. Larger, more efficient, and better regulated electric power systems are being developed. To provide large quantities of well regulated electric power more efficiently, a 270 VDC generation system is being developed along with dc-to-dc switching regulators. The negative impedance characteristics of these switching regulators along with high rate pulse loads necessitates an in-depth analytical study of all the interactive system parameters to assure power system reliability and stability under all operating environments such as combat damage, lightning and EMP.

An essential tool for the development and analysis of an HVDC System is a general purpose computer program for dynamic simulation and analysis. To provide this dynamic simulation and analysis capability, the Boeing Military Airplane Company (BMAC) was awarded a contract to install the EASY program on the NADC computer and to create an HVDC component library for the EASY Model Generation and Analysis Computer Program.

This report details the development of the HVDC system component models and their application on the EASY general purpose computer program for dynamic simulation and analysis.

1.2 EASY Model Generation and Analysis Program

The EASY model generation and analysis program used to evaluate the HVDC components in various system configurations is a powerful and flexible tool for performing complex dynamic system simulations and analyses.

EASY is not, in itself, a simulation or model of any physical system. It is instead, a means of attaching:

- o Predefined Subsystem Models
- o New Subsystem Models, and
- o Analytical Subprograms

to a well-developed and flexible software structure. The resulting computer program is a model of the system of interest that is custom tailored to the user's needs.

The EASY computer program was discussed in detail at the NADC EASY Usage Seminar presented by Boeing on May 19 through 23, 1980, as part of this contract. Documentation was delivered to the Navy at that time which detailed the operation and usage of the EASY program and which detailed the application of HVDC system models on the program (reference 1 and 2). The program was also installed on the NADC computer system at that time as specified in the contract. The Appendix of this report includes general information regarding the EASY program and its usage.

1.3 Program Objective

The objective of this contract was to develop versatile mathematical models, for the major components of the 270 VDC aircraft electrical power system. These models were developed and converted to EASY Standard Component format so that the system model can be generated and analysed using the EASY program. The specific components for which models were developed are:

1. 270 VDC solid rotor generator and solid state voltage regulator.

2. 270 VDC wound rotor generator and solid state voltage regulator.

3. Two conductor flat power distribution bus with a variable width-to-thickness (w/t) ratio of between 100 and 200.

4. Buck type switching regulator

5. EMI switching regulator filter

6. Electrical loads typical of aeronautical applications such as lighting and pulse type loads.

1.4 Approach

This program was conducted in four tasks as follows:

TASK 1 Technology Survey

TASK 1 of the contract required a general survey of industry and the military literature to find system and/or component computer models which would be applicable to HVDC system simulations, and also to determine problem areas associated with each component that should be reflected in the computer models.

TASK 2 EASY Program Installation and Checkout

TASK 2 of the contract required a magnetic tape to be prepared which contained all the EASY program code and the existing electrical system component library code. The tape was then installed on NADC Computers and checked out with a known test case prepared by Boeing.

TASK 3 HVDC System Component Model Development

TASK 3 of the contract required the development of HVDC system mathematical modelling components consisting of a DC wound rotor generator with regulator model, a DC solid rotor generator with regulator model, a switching regulator with EMI input filter model, a two conductor flat power distribution bus model, and electrical load models. Each of the component models was developed in a manner that allows them to interface for overall system simulations. TASK 3 also required the simulation of HVDC systems with simulation results presented and compared with available test results.

TASK 4 Program Operation and Model Utilization Demonstration and Instruction

TASK 4 of the contract required the preparation of an EASY program user's manual and to conduct a four-day course to train the NADC personnel in the use of the EASY program and the HVDC component models.

1.5 Results

Computer models of the major components of the HVDC system have been developed. These models have been checked-out individually and in system simulation. The component responses were compared to the limited data available and reasonable correlation was obtained.

Four dynamic simulations were accomplished on the following models.

The first model, a buck switching regulator interfaced with an RLC load, was initially operating with a continuous load of 20 volts at 2 amps. The load demand was switched to 10 amps. The switching regulator model maintained its output voltage at 20 volts while increasing its current supplied to the load to 10 amps. The small voltage transient created by the load application had no apparent affect on system stability.

The second model, a buck switching regulator with a lighting load was included to show the model response to high impulse current demands. The model was switched on with a 600 watt lighting load connected. A 160 amp current spike did not create any system instabilities.

The third model, a complete HVDC system, included a wound rotor-type generation system, a flat two-conductor distribution system, a buck switching regulator with an EMI filter and an RLC load. Initially the distribution system was supplying 30 volts at 85 amps with 65 amps continuous at bus 1, and 20 amps through the switching regulator to an RLC load at bus 2.

The load demand at bus 1 was switched to 85 amps and the RLC load was switched to reflect a 40 amp demand. The generated voltage transients created by the load changes had no apparent affect on system stability, with the transients being damped out within a few microseconds and the system continuing to operate in a stable mode.

The fourth model was similar to the third model described above except the generation system was replaced with a solid rotor type generation system. Also the voltage supplied in this case was increased to 270 VDC. The other components remained the same. Initially the generation system was supplying 270 VDC at 40 amps. This 40 amps was distributed to bus 1 which had a switching regulator with RLC load. Bus 2 had no loads applied in this initial period. The load demand was switched to 50 amps at bus 1 and 60 amps at bus 2. A large voltage transient was generated at the generator terminals, however, these system transients damped out within a few microseconds with the system continuing to operate in a stable mode.

1.6 Conclusions and Recommendations

It can be concluded that the system components developed for the HVDC model simulations operate in a stable mode when simulated with the input parameter data provided by the component vendor or the Navy. The dynamic responses of each component, as computed in the simulations conducted on the HVDC system models, correlated with the limited data available.

It is recommended that the models developed in this program be verified by comparing their responses to the responses of actual hardware as this test data becomes available.

SECTION II

HVDC SYSTEM MODELLING COMPONENTS DEVELOPMENT

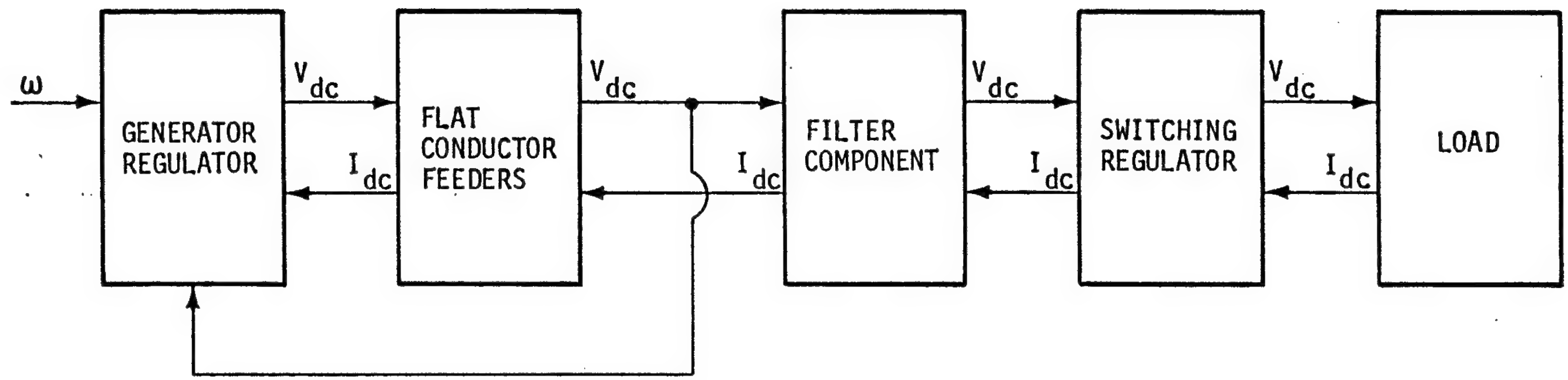
The major components of the HVDC system modelled for computer simulation are the switching regulator with EMI input filter, the load components, the wound rotor and solid rotor generators with their solid state regulators and the flat conductor distribution bus. The overall system model in block diagram form is shown in figure 1. Each of these component models was developed in three basic steps:

1. Determine mathematical equations which best define the model.

2. Develop an EASY standard component which represents these mathematical equations.

3. Verify the EASY standard components with existing data (i.e., hardware or computer simulation) available or as provided by NADC.

Each of the system components with regard to items 1 and 2 are discussed in detail in the following paragraphs with item 3 and computer simulations discussed in Section 3.



GEN/REG:

32 VDC   WOUND ROTOR GENERATOR/REGULATION LOOP

270 VDC   SOLID ROTOR GENERATOR/REGULATOR LOOP

FEEDER:

TWO CONDUCTOR FLAT POWER
DISTRIBUTION BUS

FILTER:

TWO STAGE INPUT EMI
FILTER FOR SWITCHING REG.

SWITCHING REG:

MULTIPLE CONTROL LOOP
BUCK SWITCHING REGULATOR

LOAD:

ELECTRICAL RLC NETWORK
LIGHTING CIRCUIT

Figure 1 HVDC System Block Diagram

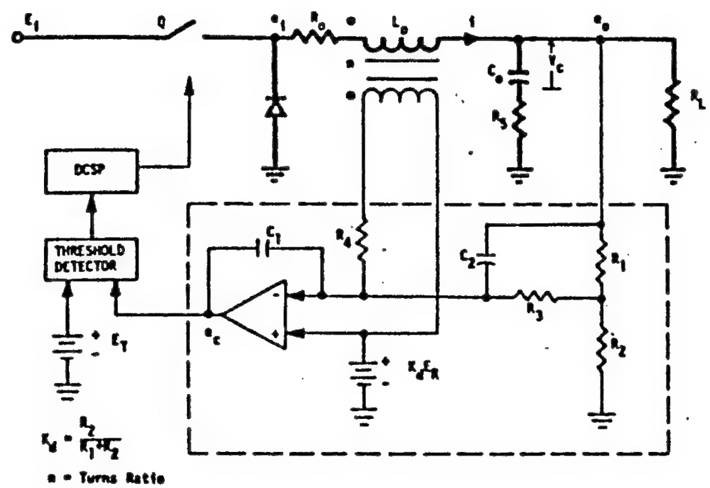
2.1 SWITCHING REGULATOR

Over the past several years the analysis of switching regulators has been undertaken in great depth to develop models that accurately describe the various types of switching regulators for improving their design. Although we have reviewed a great deal of the information available, the following documents were studied in particular detail as they seemed to apply directly to our task. These include the MAPPS study (reference 3) and several papers referenced by and included in the MAPPS study report (references 4, 5, 6, 7), the concurrent work done in reference 8 and the works of R. D. Middlebrook and Dr. S. Cuk (reference 9) as presented at the PESC, June 1979.

The time domain modelling of the switching regulators presented in the MAPPS study has been the basis of our regulator modelling. It is apparent that although many models and modelling techniques have been derived, no one model has been developed that can be used for an end-to-end system simulation that we desire. We have based our model of the buck switching regulator, shown in figure 2, on the state equations defined for the series switched regulator by R. I. Iwens, Y. Yu, and J. E. Triner in references 3, 4, 9. Also, we are using modified integral pulse frequency modulation (IPFM) equations to describe the digital control signal processor (DCSP) based on Section II of reference 4. The work done by Y. Yu, R. I. Iwens, F. C. Lee, and L. Y. Inouye in reference 10 shows the validity of the model.

The model state equations are similar to those used in reference 4 since the equations are written as first order differential equations as required by the EASY program, our analysis tool. The DCSP equations are simple logic equations that compare the error signal with a threshold level to open or close the regulator switch at varying time intervals.

Series Switched Regulator



State Equations

$$\dot{i} = \frac{1}{L_o}(e_1 - e_o - R_o i)$$

$$\dot{e}_o = e_o\left(-\frac{1}{C_o(R_5+R_L)} - \frac{R_5R_L}{L_o(R_5+R_L)}\right) + i\left(\frac{1}{C_o(R_5+R_L)} - \frac{R_oR_5R_L}{L_o(R_5+R_L)}\right) + e_1\left(\frac{R_5R_L}{L_o(R_5+R_L)}\right)$$

$$\dot{e}_c = \left(\frac{n}{R_4C_1} - \frac{K_d}{R_3C_1}\right)e_o - \frac{C_2}{C_1}\dot{e}_o + \frac{K_d}{R_3C_1}E_R - \frac{n}{R_4C_1}e_1 + \frac{nR_o}{R_4C_1}i$$

$$e_1 = \begin{cases} E_1 \text{ when switch Q is closed} & (e_c > E_T) \\ 0 \text{ when switch Q is open} & (e_c < E_T) \end{cases}$$

Figure 2 Buck Switching Regulator Schematic

2.1.1 Formulation of Equations

The buck switching regulator as shown in figure 2 has three states which are defined as follows: the output voltage e_o, the current i flowing through the inductance L_o, and the voltage output e_c of the integrator. The following basic equations are therefore obtained (the control network impedance is assumed infinite to the load as in reference 4).

$$\frac{di}{dt} = \frac{1}{L_o} (e_i - e_o - R_o\, i) \tag{1}$$

$$e_o = R_5 \left(i - \frac{e_o}{R_L}\right) + V_c \tag{2}$$

$$\frac{dv_c}{dt} = \frac{i}{C_o} - \frac{e_o}{R_L\, C_o} \tag{3}$$

Differentiating e_o in equation (2) with respect to time, and substituting for di/dt and dV_c/dt from (1) and (3) yields the following:

$$\frac{de_o}{dt} = e_o - \frac{1}{C_o(R_5 + R_L)} - \frac{R_5\, R_L}{L_o(R_5 + R_L)}$$

$$+ \; i \; \frac{R_L}{C_o(R_5 + R_L)} - \frac{R_o\, R_5\, R_1}{L_o(R_5 + R_L)} + e_i\, \frac{R_5\, R_L}{L_o(R_5 + R_L)} \tag{4}$$

Equations (1) and (4) are the state equations of the power circuit. The control voltage through the integrator, differentiated with respect to time, yields:

$$\frac{de_c}{dt} = \frac{n}{R_4\, C_1} - e_o\, \frac{K_d}{R_3\, C_1} - \frac{C_2}{C_1}\, \frac{de_o}{dt} + E_R\, \frac{K_d}{R_3\, C_1} \tag{5}$$

The voltage e_c of this third state equation of the regulator is then compared with some predefined threshold level voltage E_T and becomes the point of reference for the pulse modulator that controls the power switching transistor Q. By opening and closing the transistor switch, the output voltage e_0 is maintained at some specified reference voltage E_R.

A flow chart which shows the computational technique used in the computer model of the Digital Control Signal Processor (DCSP) is shown in figure 3.

The basic difference between our model and other time domain switching regulator models available is the control of switch Q. For our applications of the model, specifically, digital computer simulations under transient conditions, the switch has both a variable on-time and variable off-time with a built in delay of a prespecified minimum time on and minimum time off. This type of switching function thus has good correlation with switching regulator operation as seen in the simulation section of this report (Section III).

All states, variables, and parameters are defined in the switching regulator input/output list shown in figure 4.

2.1.2 EASY Standard Component, S4

S4 is the EASY standard component representation of the buck-switching regulator. As in all EASY standard components, the S4 component is a Fortran subroutine that meets the specific requirements of the EASY program as defined in reference 2. The EASY Standard Component Subroutine listing of the buck switching regulator is shown in figure 5. All symbols used in the component are defined in the subroutine listing and the input/output listing of S4 and specifically described below as they relate to the schematic of the switching regulator shown in figure 2.

Required Inputs of the S4 Component

The central element of the regulator, switch Q, is controlled by the DC and AC control loops defined by the input parameters TS, minimum regulator on-time; TR, minimum regulator off-time; ET, control threshold voltage; ER, desired output voltage; R1 through R4, control circuit resistances; C1 and C2, control circuit capacitors; and N, the AC control circuit turns ratio.

EQUIVALENT NONLINEAR DISCRETE TIME SYSTEM FLOW DIAGRAM

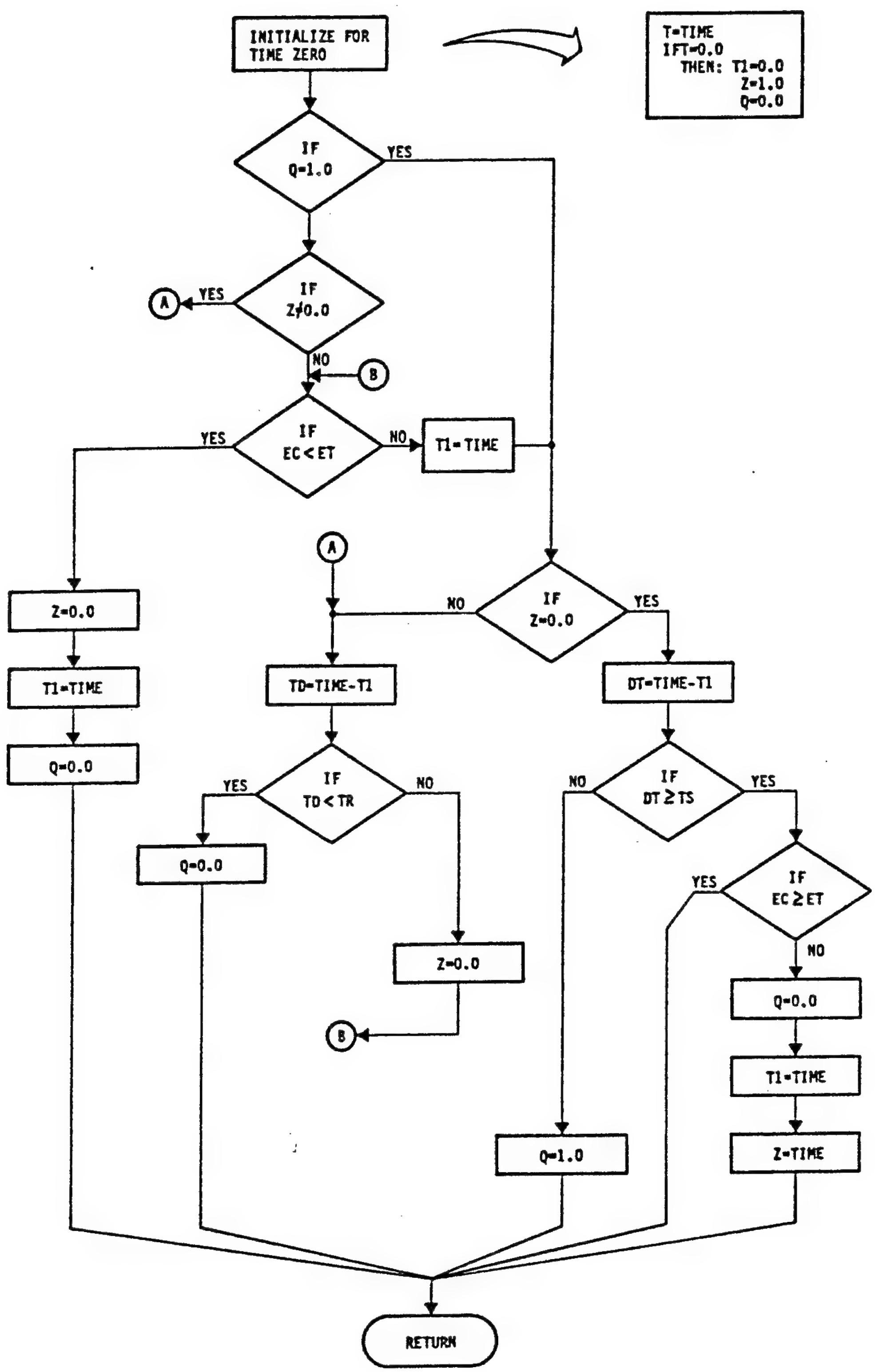


Figure 3 Digital Control Signal Processing Flow Chart

S4

BUCK SWITCHING REGULATOR

INPUTS

TS	REG.SWITCH TIME ON (MINIMUM)	SEC
TR	REG.SWITCH TIME OFF(MINIMUM)	SEC
ET	REGULATOR THRESHOLD VOLTAGE	VOLTS
ER	REFERENCE(DESIRED OUTPUT)	VOLTS
RO	INDUCTOR SERIES RESISTANCE	OHMS
R1	VOLTAGE DIVIDER RESISTOR	OHMS
R2	VOLTAGE DIVIDER RESISTOR	OHMS
R3	OP-AMP DC INPUT RESISTOR	OHMS
R4	OP-AMP AC INPUT RESISTOR	OHMS
R5	SERIES RESISTANCE OF CO	OHMS
RL	SERIES LOAD	OHMS
LO	OUTPUT FILTER INDUCTOR	HENRIES
CO	OUTPUT FILTER CAPACITOR	FARADS
C1	OP-AMP FEEDBACK CAPACITOR	FARADS
C2	LOAD COMPENSATION CAPACITOR	FARADS
N	TRANSFORMER TURNS RATIO	------

OUTPUTS

ALO *	INDUCTOR CURRENT	AMPS
EO *	REGULATOR OUTPUT	VOLTS
X1 *	INTERMEDIATE STATE	-----
EC	REGULATOR ERROR VOLTAGE	VOLTS
T	TIME	SEC
T1	TIME	SEC
Z	TIME	SEC
Q	DCSP OUTPUT	-----
TD	DIFFERENTIAL TIME	SEC
DT	DIFFERENTIAL TIME	SEC
KD	VOLTAGE DIVIDER RATIO	-----

* State Variables

Figure 4 Switching Regulator Component (S4) Input/Output List

```
CS4
      SUBROUTINE S4(ALO,ALODOT,IALO,XO,XODOT,IXO,X1,X1DOT,IX1,
     1 EO,EC,T1,Z,Q,TD,DT,KD,T,TS,TR,ET,EI,R1,LO,CO,RO,R2,R3,R4,
     2 R5,AL,C1,C2,ER,N)
C
C     BUCK SWITCHING REGULATOR MODEL
C     WRITTEN BY D.SOMMER
C     LATEST REVISION--2/15/80
C
C              INPUT/OUTPUT LIST
C
C  SYMBOL            NAME                         UNIT      ELEMENT TYPE
C
C  ALO         INDUCTOR CURRENT                   AMPS      OUTPUT STATE
C  XO          INTERMEDIATE STATE                 ----      OUTPUT STATE
C  X1          INTERMEDIATE STATE                 ----      OUTPUT STATE
C
C  EO          REGULATOR OUTPUT                   VOLTS     OUTPUT VARIABLE
C  EC          REGULATOR ERROR VOLTAGE            VOLTS     OUTPUT VARIABLE
C  T           TIME                               SEC       OUTPUT VARIABLE
C  T1          TIME                               SEC       OUTPUT VARIABLE
C  Z           TIME                               SEC       OUTPUT VARIABLE
C  Q           DCSP OUTPUT                        ----      OUTPUT VARIABLE
C  TD          DIFFERENTIAL TIME                  SEC       OUTPUT VARIABLE
C  DT          DIFFERENTIAL TIME                  SEC       OUTPUT VARIABLE
C  KD          VOLTAGE DIVIDER RATIO              ----      OUTPUT VARIABLE
C
C  TS          REG.SWITCH TIME ON (MINIMUM)       SEC       INPUT PARAMETER
C  TR          REG.SWITCH TIME OFF(MINIMUM)       SEC       INPUT PARAMETER
C  ET          REGULATOR THRESHOLD VOLTAGE        VOLTS     INPUT PARAMETER
C  ER          REFERENCE(DESIRED OUTPUT)          VOLTS     INPUT PARAMETER
C  RO          INDUCTOR SERIES RESISTANCE         OHMS      INPUT PARAMETER
C  R1          VOLTAGE DIVIDER RESISTOR           OHMS      INPUT PARAMETER
C  R2          VOLTAGE DIVIDER RESISTOR           OHMS      INPUT PARAMETER
C  R3          OP-AMP DC INPUT RESISTOR           OHMS      INPUT PARAMETER
C  R4          OP-AMP AC INPUT RESISTOR           OHMS      INPUT PARAMETER
C  R5          SERIES RESISTANCE OF CO            OHMS      INPUT PARAMETER
C  LO          OUTPUT FILTER INDUCTOR             HENRIES   INPUT PARAMETER
C  CO          OUTPUT FILTER CAPACITOR            FARADS    INPUT PARAMETER
C  C1          OP-AMP FEEDBACK CAPACITOR          FARADS    INPUT PARAMETER
C  C2          LOAD COMPENSATION CAPACITOR        FARADS    INPUT PARAMETER
C  N           TRANSFORMER TURNS RATIO            ----      INPUT PARAMETER
C
C  AL          LOAD CURRENT                       AMPS      INPUT VARIABLE
C
      REAL N,LO,KD
      COMMON/CTIME/TIME
C  INITIALIZE TIME
      T=TIME
C  COMPUTE REGULATOR OUTPUT VOLTAGE
      EO=-R5*AL+XO
C  COMPUTE CONTROL ERROR VOLTAGE
      EC=X1-EO*C2/C1
C  COMPUTE CONDITION OF SWITCH Q
C  BY COMPARING TIME WITH MINIMUM
C  ON-TIME AND MINIMUM OFF-TIME
```

Figure 5 Switching Regulator Component (S4) Subroutine Listing

```
C  USER SPECIFIED PARAMETERS,TS AND TR
      IF(T.NE.0.0) GO TO 20
      T1=0.0
      Z=1.0
      Q=0.0
   20 IF(Q.EQ.1.0) GO TO 30
      IF(Z.NE.0.0) GO TO 35
   25 IF(EC.LT.ET) GO TO 60
      T1 = TIME
   30 IF(Z.EQ.0.0) GO TO 40
   35 TD=TIME-T1
      IF(TD.LT.TR) GO TO 70
      Z=0.0
      GO TO 25
   40 DT=TIME-T1
      IF(DT.GE.TS) GO TO 50
      Q=1.0
      GO TO 80
   50 IF(EC.GE.ET) GO TO 80
      Z=TIME
      GO TO 65
   60 Z=0.0
   65 T1=TIME
   70 Q=0.0
C  COMPUTE DC ERROR CONTROL VOLTAGE RATIO
   80 KD=R2/(R1+R2)
C  TEST FOR DISCONTINUOUS MODE OPERATION
      IF(ALO.LE.0.0) ALO=0.0
C  COMPUTE REGULATOR STATE VARIABLES
      ALODOT=(Q*EI-EO-RO*ALO)/LO
      XODOT=EI*Q*(R5/LO)+ALO*(1/CO-RO/LO)-EO*R5/LO-AL/CO
      X1DOT=EO*(N/(R4*C1)-KD/(R3*C1))+KD*ER/(R3*C1)
     1 -N*EI*Q/(R4*C1)+N*RO*ALO/(R4*C1)
      RETURN
      END
```

Figure 5 Switching Regulator Component (S4) Subroutine Listing (Continued)

The switching regulator current and voltage are maintained by the parameters LO and RO, the regulator output filter inductance, and winding resistance; and CO and R5, the regulator output filter capacitance and its associated resistance. The component also requires AL, the load current in amps and EI, the regulator input voltage in volts. AL and EI inputs are either a fixed value for stand alone regulator analysis or a variable value for system (multiple component) analysis as specified in the model generation portion of the EASY program.

Computed Outputs of the S4 Component

There are three state variables for the component S4. The state ALO represents the current through the inductor LO. The states XO and X1 are considered intermediate state variables. They are derived from the system state equations using basic mathematical manipulations to meet the requirement of the EASY program that the state equations must be of the first order form. The state XO is algebraically proportional to EO, the switching regulator output voltage. The state X1 is algebraically proportional to EC, the switching regulator error control voltage. The voltage EC is compared with the input parameter ET to provide voltage level input information to the DCSP which determines the on and off time of the regulator power switch, Q. The other output variables T, T1, TD and DT are real time dependent and are used to modulate the regulator power switch, as shown in the flow diagram in figure 3.

The validity of the switching regulator model can be seen in the simulation section (Section III). The dynamic simulation test cases compare favorably with those of reference 4.

2.2 SWITCHING REGULATOR EMI FILTER

With switching-mode power supplies LC, low-pass decoupling filters are inserted between the prime mover and the regulator to keep switching transients off the power bus. An improperly designed input filter, however, can cause interactions between the input filter and the control loop of the switching regulator and cause regulator degradation (reference 7).

In switching-regulator type devices, feedback control and feed-forward compensation are used to make the output relatively independent of the input voltage. When coupled with an LC filter a negative input resistance characteristic is created. This may cause oscillating currents that can over stress the filter, can cause the source to malfunction or may be coupled into other equipment via the source impedance or via magnetic coupling to the power lines (references 11, 12 and 13).

The EMI filter used for our modelling is a two stage low pass filter network similar to that used in the MAPPS study (reference 3, 14). The filter model is comprised of capacitive, inductive and resistive elements.

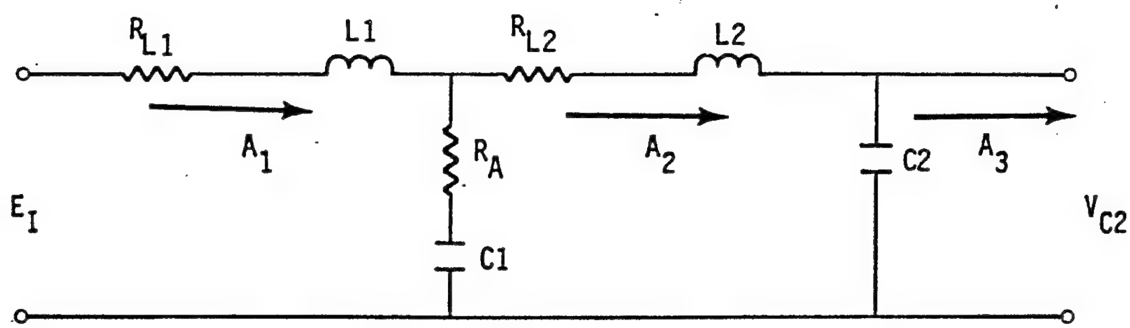
2.2.1 Formulation of Equations

The EMI filter representation as shown in figure 6 has four states which are defined as follows: the input inductor current, A_1; the output inductor current, A_2; the voltage, V_1 developed across the input capacitor; and the voltage V_2 developed across the output capacitor. The following equations are then derived from the schematic of the filter shown in the figure. (Note that R_1, R_2, and R_A are resistive values associated with the inductors and capacitor respectively.

Currents through inductors

where E_I is the source voltage

$$\frac{dA_1}{dt} = \frac{1}{L_1} \quad (E_I - R_1A_1 - R_A (A_1 - A_2) - V_1) \tag{6}$$



STATE EQUATIONS:

$$\frac{dA_1}{dt} = \frac{1}{L_1} \left(E_I - R_{L1} A_1 - R_A (A_1 - A_2) - V_{C1}\right.$$

$$\frac{dV_{C1}}{dt} = \frac{1}{C_1} (A_1 - A_2)$$

$$\frac{dA_2}{dt} = \frac{1}{L_2} \left(V_{C1} + R_A (A_1 - A_2) - R_{L2} A_2 - V_{C2}\right.$$

$$\frac{dV_{C2}}{dt} = \frac{1}{C_2} (A_2 - A_3)$$

Figure 6 Switching Regulator EMI Filter Schematic

$$\frac{dA_2}{dt} = \frac{1}{L_2} \qquad (V_1 + R_A (A_1 - A_2) - R_2A_2 - V_2) \qquad (7)$$

Voltages across the capacitors
where A_3 is the load current

$$\frac{dV_1}{dt} = \frac{1}{C_1} \qquad (A_1 - A_2) \qquad (8)$$

$$\frac{dV_2}{dt} = \frac{1}{C_2} \qquad (A_2 - A_3) \qquad (9)$$

All states and parameters of the EMI filter model are defined in the input/output listing shown in figure 7.

2.2.2 EASY Standard Component, F4

F4 is the EASY standard component representation of the switching regulator EMI filter model. The component is a Fortran subroutine that meets the specific requirements of the EASY program (reference 2). The EASY standard component subroutine listing of the filter model is shown in figure 8. All symbols used in the component are defined in this subroutine listing and in the input/output listing of F4 and specifically described below as they relate to the schematic of the filter shown in figure 6.

<u>Required Inputs of the F4 Component</u>

The F4 Component requires the following input parameters which represent filter design data either computed for engineering studies or supplied by vendors. L1 and L2 are the filter inductance values and R1 and R2 are their corresponding resistance values. C1 and C2 are the filter capacitance values and RA the capacitor equivalent series resistance.

EMI FILTER

INPUTS

EI	INPUT VOLTAGE	VOLTS
A3	LOAD CURRENT	AMPS
L1	INDUCTANCE	HENRIES
L2	INDUCTANCE	HENRIES
C1	CAPACITANCE	FARADS
C2	CAPACITANCE	FARADS
RA	CAPACITOR EFFECTIVE RESISTANCE	OHMS
R1	INDUCTOR EFFECTIVE RESISTANCE	OHMS
R2	INDUCTOR EFFECTIVE RESISTANCE	OHMS

OUTPUTS

A1 *	INPUT INDUCTOR CURRENT	AMPS
A2 *	OUTPUT INDUCTOR CURRENT	AMPS
V1 *	VOLTAGE ACROSS INPUT CAPACITOR	VOLTS
V2 *	VOLTAGE ACROSS OUTPUT CAPACITOR	VOLTS

* State Variables

EQUATIONS:

$$A1=(1/L1)*(EI-R1*A1-RA*(A1-A2)-V1)$$

$$V1=(1/C1)*(A1-A2)$$

$$A2=(1/L2)*(V1+RA*(A1-A2)-R2*A2-V2)$$

$$V2=(1/C2)*(A2-A3)$$

Figure 7 EMI Filter Component (F4) Input/Output List

```
CF4
C
      SUBROUTINE F4(A1,A1DOT,IA1,V1,V1DOT,IV1,V2,V2DOT,IV2,
     1 A2,A2DOT,IA2,EI,A3,L1,L2,C1,C2,RA,R1,R2)
C
C     TWO STAGE FILTER
C     WRITTEN BY D.SOMMER
C     LATEST REVISION--1/3/80
C
C                       INPUT/OUTPUT LIST
C
C  SYMBOL              DEFINITION                  UNIT        ELEMENT TYPE
C
C  A1         INPUT INDUCTOR CURRENT               AMPS        OUTPUT STATE
C  A2         OUTPUT INDUCTOR CURRENT              AMPS        OUTPUT STATE
C  V1         VOLTAGE ACROSS INPUT CAPACITOR       VOLTS       OUTPUT STATE
C  V2         VOLTAGE ACROSS OUTPUT CAPACITOR      VOLTS       OUTPUT STATE
C
C  EI         INPUT VOLTAGE                        VOLTS       INPUT VARIABLE
C  A3         LOAD CURRENT                         AMPS        INPUT VARIABLE
C
C  L1         INDUCTANCE                           HENRIES     INPUT PARAMETER
C  L2         INDUCTANCE                           HENRIES     INPUT PARAMETER
C  C1         CAPACITANCE                          FARADS      INPUT PARAMETER
C  C2         CAPACITANCE                          FARADS      INPUT PARAMETER
C  RA         CAPACITOR EFFECTIVE RESISTANCE       OHMS        INPUT PARAMETER
C  R1         INDUCTOR EFFECTIVE RESISTANCE        OHMS        INPUT PARAMETER
C  R2         INDUCTOR EFFECTIVE RESISTANCE        OHMS        INPUT PARAMETER
C
C
      REAL L1,L2
C
C  CALCULATE STATE VARIABLES
      A1DOT=(1/L1)*(EI-R1*A1-RA*(A1-A2)-V1)
      V1DOT=(1/C1)*(A1-A2)
      A2DOT=(1/L2)*(V1+RA*(A1-A2)-R2*A2-V2)
      V2DOT=(1/C2)*(A2-A3)
      RETURN
      END
```

Figure 8 EMI Filter Component (F4) Subroutine Listing

Variable inputs for the filter component are the line Voltage EI, which is the interface variable between the flat conductor component and the filter component; and the load current AL, which is the interface variable between the switching regulator component and the filter component. For stand alone filter analysis EI and AL can be input by the user as parameter values.

Computed Outputs of the F4 Component

The two-stage filter component has four computed state variables, one for each of the filter inductors, currents A1 and A2; and one for each of the filter capacitors, voltages V1 and V2. The voltage variable V2 interfaces with the switching regulator component. The current variable A2 interfaces with the flat conductor feeder component.

2.3 WOUND ROTOR DC GENERATOR/REGULATOR

There have been several analog computer models developed of wound rotor machines varying in complexity depending on the detail required for the specific analysis. Many of these models can be simulated on a digital computer by rewriting the equations for application to one of the available analysis computer programs such as EASY. Boeing has been analyzing several of these models using the EASY program such as the analysis of EASY AC machines described in reference 15. These and other machine analog models are described in detail in reference 16.

For the modelling of the HVDC wound rotor generation system (this system consists of a DC generator with rectifiers and filter, and a voltage regulator), the Lear Siegler control loop model (reference 17) of a low voltage DC machine seemed to be most applicable to our analysis. The techniques used in their model to approximate the generation system were the same as those used in reference 16. Also, Lear Siegler is using basically the same control loop to define their high voltage 270 VDC generation system. Since a high voltage machine model is required for our analysis, their DC machine control loop model is used in our analysis.

2.3.1 Formulation of Equations

The DC wound rotor generation system as shown in figure 9 has seven states which are defined as follows: The output voltage V_0 (filtered DC voltage), the generator main field current A_F, the exciter current A_{EX}, the second order voltage regulator states V_R and X_R, and the second order exciter feedback states V_R and X_F. The following basic equations can then be derived from the transfer functions of figure 9. (Note that W represents the generator operating speed, G represents system gains and T represents system time constants).

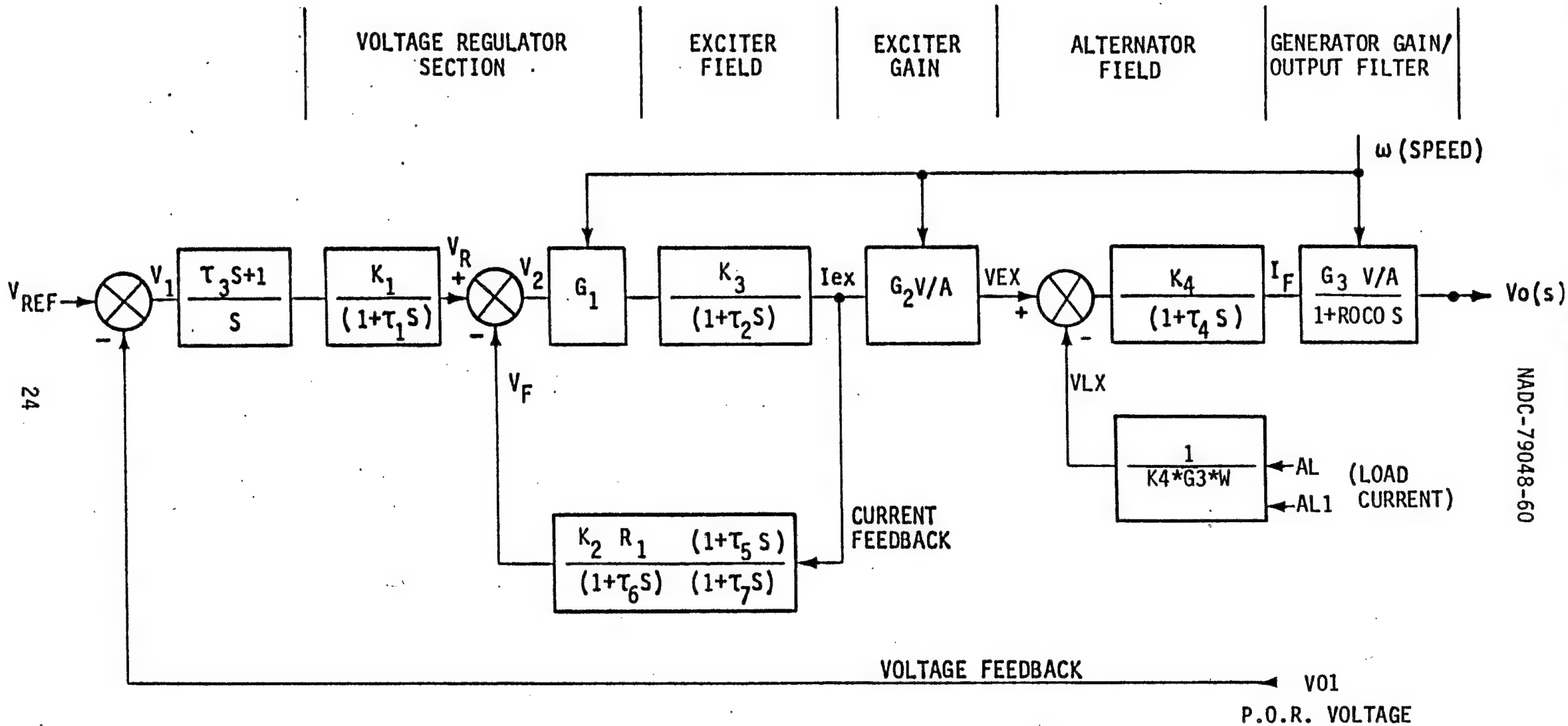


Figure 9 Generation System with Wound Rotor Generator Component

Output Voltage:

$$\frac{dV_0}{dt} = (A_F\ G_3\ W - V_0)\ \frac{1}{R_0\ C_0} \tag{10}$$

Main Field Current:

$$\frac{dA_F}{dt} = (K_4\ V_{EX} - A_F)\ \frac{1}{T_4} \tag{11}$$

Exciter Current:

$$\frac{dA_{EX}}{dt} = (W\ G_1 K_3\ V_2 - A_{EX})\ \frac{1}{T_2} \tag{12}$$

Regulator Voltages:

$$\frac{dX_R}{dt} = K_1 V_1 \tag{13}$$

$$\frac{dV_R}{dt} = (K_1\ T_3\ V_1 + X_R - V_R)\ \frac{1}{T_1} \tag{14}$$

Exciter Feedback Voltages:

$$\frac{dX_F}{dt} = (K_2\ R_1\ A_{EX} - V_F) \tag{15}$$

$$\frac{dV_F}{dt} = (K_2\ R_1\ T_5\ A_{EX} + X_F - V_F)\ \frac{1}{T_6} \tag{16}$$

Exciter Voltage:

$$V_{EX} = G_2\ W\ A_{EX} - V_{LX} \tag{17}$$

(where V_{LX} is the load feedback voltage directly proportional to the load current)

The DC generator/regulator control loop which these equations describe form the wound rotor DC generation system model.

Since in the DC system the generator output is isolated from line perturbations by the rectifiers and filter components, these perturbations will have the greatest influence on the regulation elements of the generation system components. The generator transfer function then becomes an integral part of the regulation loop as seen in the figure.

All states, variables, and parameters of the wound rotor generation system model are defined in the input/output listing shown in figure 10.

2.3.2 EASY Standard Component, W4

W4 is the EASY standard component representation of the wound rotor generation system model. The W4 component is a Fortran subroutine that meets the specific requirements of the EASY program as defined in reference 2. The EASY standard subroutine listing of the Wound Rotor Generation System is shown in figure 11. All symbols used in the component are defined in the subroutine listing and the input/output listing of W4 and specifically described below as they relate to the diagram of the wound rotor generation system shown in figure 9.

Required Inputs of the W4 Component

The W4 component requires the following input parameters which represent system data either available directly from the vendors or calculated from vendor data. W is the generator operating speed in radians per second and is typically a constant value within the nominal operating range of the specific machine. T4 is a time constant of the transfer function which represents the wound rotor DC generator. T2 is a time constant of the transfer function which represents the generator exciter. The generated exciter current is fed through a second order lead-lag network with time constants T5, T6, and T7 to the voltage regulator. T1 is the time constant of the transfer function which represents the voltage regulator and T3 is the time constant of the compensation network which provides the inputs to the voltage regulator.

DC WOUND ROTOR GENERATOR-REGULATOR

W4

INPUTS

W	GENERATOR SPEED	RADS/SEC
VI	REGULATOR REFERENCE VOLTAGE	VOLTS
T1	REGULATOR TIME CONSTANT	SEC
T2	EXCITER TIME CONSTANT	SEC
T3	COMPENSATION TIME CONSTANT	SEC
T4	GENERATOR TIME CONSTANT	SEC
T5	CONTROL LOOP TIME CONSTANT	SEC
T6	CONTROL LOOP TIME CONSTANT	SEC
T7	CONTROL LOOP TIME CONSTANT	SEC
G1	REGULATOR GAIN	V-SEC/AMP
G2	EXCITER GAIN	V-SEC/AMP
G3	RECTIFIED GENERATOR GAIN	V-SEC/AMP
K1	REGULATOR CONSTANT	-----
K2	CONTROL LOOP CONSTANT	-----
K3	INVERTED EXCITER RESISTANCE	1/OHM
K4	INVERTED GEN. FIELD RESISTANCE	1/OHM
R1	CONTROL LOOP RESISTANCE	OHMS
RO	EFFECTIVE RECTIFIER RESISTANCE	OHMS
CO	GENERATOR OUTPUT CAPACITOR	FARADS
AL	LOAD CURRENT	AMPS
AL1	LOAD CURRENT(CONTINUOUS)	AMPS

OUTPUTS

VO *	GENERATOR OUTPUT VOLTAGE	VOLTS
AEX *	EXCITER CURRENT	AMPS
VR *	REGULATOR VOLTAGE	VOLTS
XR *	INTERMEDIATE STATE	-----
VF *	EXCITER FEEDBACK VOLTAGE	VOLTS
XF *	INTERMEDITATE STATE	-----
V1	REGULATOR ERROR VOLTAGE	VOLTS
V2	EXCITER INPUT VOLTAGE	VOLTS
AF	GENERATOR FIELD CURRENT	AMPS
VEX	EXCITER VOLTAGE	VOLTS
VLX	EXCITER FEEDBACK VOLTAGE	VOLTS
ALT	TOTAL LOAD CURRENT	AMPS

* State Variables

Figure 10 Generation System Component (W4) Input/Output List

```
CW4
      SUBROUTINE W4(AF,AFDOT,IAF,AEX,AEXDOT,IAEX,VR,VRDOT,IVR,XR,
     1 XRDOT,IXR,VF,VFDOT,IVF,XF,XFDOT,IXF,VO,VODOT,IVO,
     2 V1,V2,VEX,VLX,ALT,
     3 VI,W,T1,T2,T3,T4,T5,T6,T7,G1,G2,G3,K1,K2,K3,K4,R1,AL,AL1,RO,CO,
     4 VO1)
C
C      WOUND ROTOR DC GENERATION SYSTEM MODEL
C      WRITTEN BY D.SOMMER
C      LATEST REVISION-2/21/80
C
C               INPUT/OUTPUT LIST
C
C   SYMBOL          NAME                          UNIT        ELEMENT TYPE
C
C   VO      GENERATOR OUTPUT VOLTAGE             VOLTS       OUTPUT STATE
C   AEX     EXCITER CURRENT                      AMPS        OUTPUT STATE
C   VR      REGULATOR VOLTAGE                    VOLTS       OUTPUT STATE
C   XR      INTERMEDIATE STATE                   ---         OUTPUT STATE
C   VF      EXCITER FEEDBACK VOLTAGE             VOLTS       OUTPUT STATE
C   XF      INTERMEDITATE STATE                  ---         OUTPUT STATE
C   V1      REGULATOR ERROR VOLTAGE              VOLTS       OUTPUT VARIABLE
C   V2      EXCITER INPUT VOLTAGE                VOLTS       OUTPUT VARIABLE
C   AF      GENERATOR FIELD CURRENT              AMPS        OUTPUT VARIABLE
C   VEX     EXCITER VOLTAGE                      VOLTS       OUTPUT VARIABLE
C   VLX     EXCITER FEEDBACK VOLTAGE             VOLTS       OUTPUT VARIABLE
C   ALT     TOTAL LOAD CURRENT                   AMPS        OUTPUT VARIABLE
C   W       GENERATOR SPEED                      RADS/SEC    INPUT PARAMETER
C   VI      REGULATOR REFERENCE VOLTAGE          VOLTS       INPUT PARAMETER
C   T1      REGULATOR TIME CONSTANT              SEC         INPUT PARAMETER
C   T2      EXCITER TIME CONSTANT                SEC         INPUT PARAMETER
C   T3      COMPENSATION TIME CONSTANT           SEC         INPUT PARAMETER
C   T4      GENERATOR TIME CONSTANT              SEC         INPUT PARAMETER
C   T5      CONTROL LOOP TIME CONSTANT           SEC         INPUT PARAMETER
C   T6      CONTROL LOOP TIME CONSTANT           SEC         INPUT PARAMETER
C   T7      CONTROL LOOP TIME CONSTANT           SEC         INPUT PARAMETER
C   G1      REGULATOR GAIN                       V-SEC/AMP   INPUT PARAMETER
C   G2      EXCITER GAIN                         V-SEC/AMP   INPUT PARAMETER
C   G3      RECTIFIED GENERATOR GAIN             V-SEC/AMP   INPUT PARAMETER
C   K1      REGULATOR CONSTANT                   ---         INPUT PARAMETER
C   K2      CONTROL LOOP CONSTANT                ---         INPUT PARAMETER
C   K3      INVERTED EXCITER RESISTANCE          1/OHM       INPUT PARAMETER
C   K4      INVERTED GEN. FIELD RESISTANCE       1/OHM       INPUT PARAMETER
C   R1      CONTROL LOOP RESISTANCE              OHMS        INPUT PARAMETER
C   RO      EFFECTIVE RECTIFIER RESISTANCE       OHMS        INPUT PARAMETER
C   CO      GENERATOR OUTPUT CAPACITOR           FARADS      INPUT PARAMETER
C   AL      LOAD CURRENT                         AMPS        INPUT VARIABLE
C   AL1     LOAD CURRENT(CONTINUOUS)             AMPS        INPUT
C   VO1     P.O.R. VOLTAGE (FEEDER BUS)          VOLTS       INPUT VARIABLE
C
      REAL K1,K2,K3,K4
C  CALCULATE TOTAL LOAD CURRENT
      ALT=AL+AL1
C  CALCULATE EXCITER INPUT VOLTAGE
      V2 = VR - VF
C  CALCULATE REGULATOR ERROR VOLTAGE
```

Figure 11 Generation System Component (W4) Subroutine Listing

```
      V1 = VI - VO1
C   CALCULATE LOAD FEEDBACK VOLTAGE
      VLX=ALT*K4/(G3*W)
C   CALCULATE EXCITER VOLTAGE
      VEX=G2*W*AEX-VLX
C   COMPUTE SYSTEM STATE VARIABLES
      IF(IVO.NE.0) VODOT=(AF*G3*W-VO)/(RO*CO)
      IF(IAF.NE.0) AFDOT=(K4*VEX-AF)/T4
      IF(IAEX.NE.0) AEXDOT=(W*G1*K3*V2-AEX)/T2
      IF(IXR.NE.0) XRDOT=K1*V1
      IF(IVR.NE.0) VRDOT=(K1*V1*T3+XR-VR)/T1
      IF(IXF.NE.0) XFDOT=AEX*R1*K2-VF
      IF(IVF.NE.0) VFDOT=(K2*T5*AEX*R1+XF-T7*VF)/T6
      RETURN
      END
```

Figure 11 Generation System Component (W4) Subroutine Listing

(Continued)

The generation system gain constants are G1 for the voltage regulator transfer function, G2 for the exciter transfer function, and G3 for the generator transfer function. Other required constants are the conversion coefficients K1 for the voltage regulator and K2 for the exciter feedback loop. Resistive values required are R1, the regulator control loop resistance; R0, the effective rectifier resistance; K3 the reciprocal of the effective exciter field resistance; and K4, the reciprocal of the effective generator field resistance. The capacitance value C0 is required for the generator output filter capacitor.

Variable inputs required by the W4 component are V01, the point of regulation (P.O.R.) voltage; and AL and AL1 the system load currents. These component variables are required as parameters for single component stand alone analysis or as variable inputs interfaced with other components during system analysis.

Computed Outputs of the W4 Component

There are six computed state variables for the W4 component. As shown in the subroutine listing of the W4 component, figure 11, the rates of these states are distinguished with a "DOT" designation. The state V0 is the rectified DC voltage across the output filter capacitor. The state AEX is the exciter field current which is fed to the main field of the generator and through an integrator and lag function to the voltage regulator. The next states VR and XR define the second order voltage regulation transfer function. The states VF and XF define the second order feedback voltage transfer function of the exciter to the voltage regulator.

Output variables include V1, the error voltage to the voltage regulator that is the difference between the reference voltage and the P.O.R. voltage. The variable V2 is the unamplified regulator output voltage.

The generator excitation voltage, VEX, is defined as the difference between the voltage generated by the exciter field current and the voltage, VLX, generated by the load current. The computed system current variables are ALT which represents the total load current and AF which represents the generator field current.

2.4 270 VDC SOLID ROTOR GENERATOR/REGULATOR

The 270 VDC solid rotor generator/regulator we have modelled was developed by AiResearch for the Navy. This system consists of a permanent-magnet generator, a phase-delay rectifier unit and an electronic control unit. The block diagram of this system is shown in figure 12. The permanent-magnet generator provides a variable voltage and variable frequency ac power. This power is supplied to a power converter, a 12-pulse phase-controlled rectifier, in two three-phase groups for rectification and regulation. The voltage ripple is then reduced through the use of an interphase transformer and further attenuated to the required levels by an output filter. A detailed description of the 270 VDC generator system is given in reference 18.

The mathematical model of the 270 VDC solid rotor generator/regulator is derived from the set of transfer functions that describe each of the major elements of the system as listed above.

2.4.1 Formulation of Equations

The 270 VDC solid rotor generator/regulator system as shown in figure 12 has four state variables defined as follows: the system output voltage V_0, the filter inductor current A_{L0}, the regulator control voltage V_2, and the control loop intermediate state, X_3. The following state equations can then be derived from the transfer functions. (Note: K represents gain constants and T represents time constants).

Output Voltage:

$$\frac{dV_0}{dt} = (A_{L0} - A_{LT})/C_0 \tag{18}$$

where A_{LT} is the total load current.

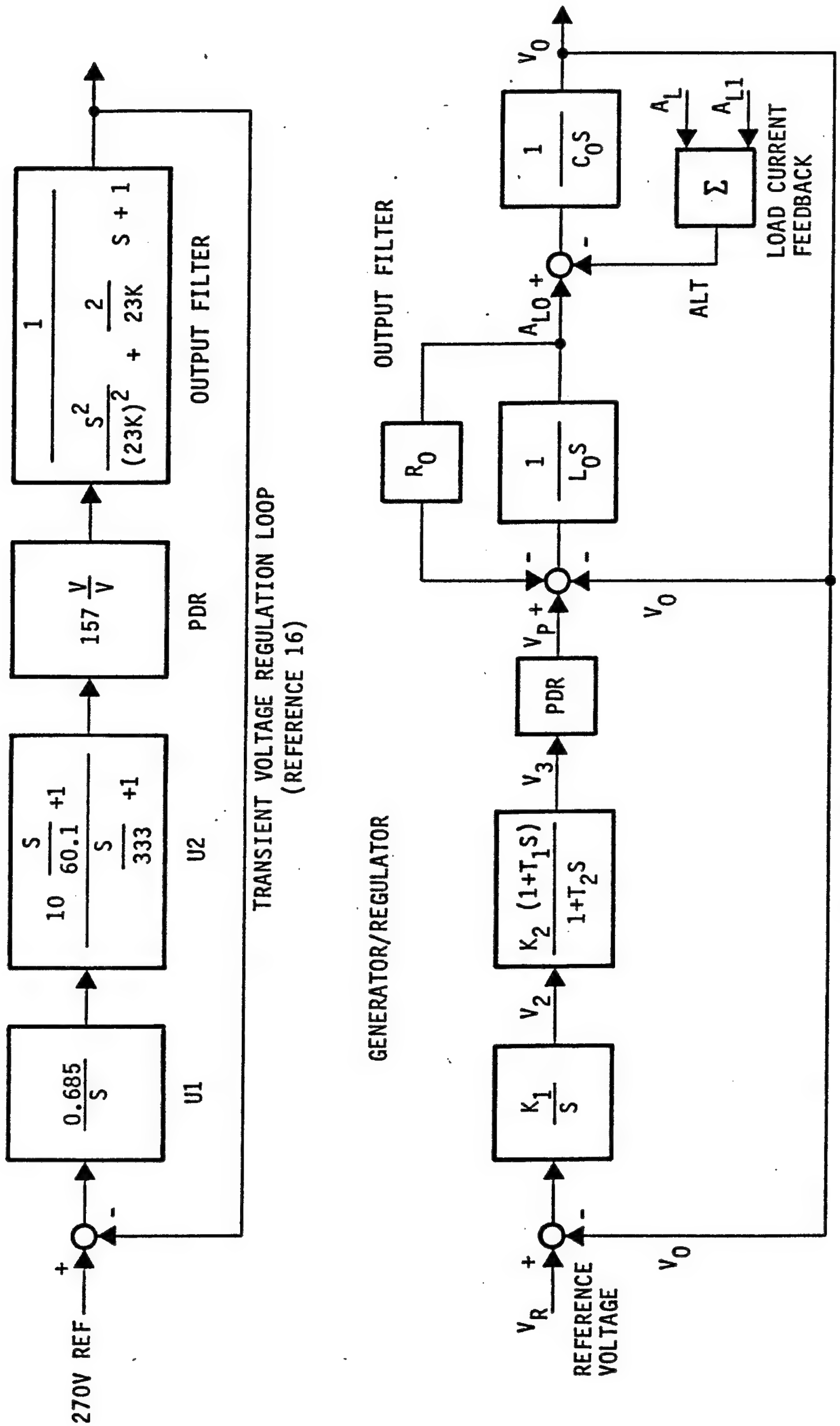


Figure 12 Generation System with Solid Rotor Generator

Inductor Current:

$$\frac{dA_{L0}}{dt} = (V_P - A_{L0} R_0 - V_0)/L_0 \qquad (19)$$

where V_P is the phase delay rectified voltage and R_0 is the effective inductor resistance.

Regulator Control Voltage:

$$\frac{dV_2}{dt} = K_1 \; V_1 \qquad (20)$$

where V_1 is the error voltage.

Control Loop State Variable:

$$\frac{dX_3}{dt} = V_2 \, K_2 - V_3 \qquad (21)$$

where V_3 is the control loop voltage.

The control loop these equations describe form the 270 VDC solid rotor generator/regulator model. A description of the AiResearch transfer function development is included in reference 18.

All states, variables, and parameters of the solid rotor system are defined in the input/output listing of the model (figure 13).

2.4.2 EASY Standard Component, G1

G1 is the EASY standard component representation of the solid rotor generation system model. The G1 component is a Fortran subroutine that meets the specific requirements of the EASY program (reference 2). The EASY standard component subroutine listing of the solid rotor generation system is shown in figure 14. All symbols used in the component are defined in the subroutine listing and the input/output listing and are specifically described below as they relate to the diagram of the solid rotor generation system shown in figure 12.

SOLID ROTOR GENERATOR-REGULATOR

INPUTS

PHYSICAL QUANTITY NAME	DESCRIPTION	UNITS
AL	LOAD CURRENT	AMPS
AL1	LOAD CURRENT (CONTINUOUS)	AMPS
VR	VOLTAGE REFERENCE	VOLTS
L1	GENERATOR INDUCTANCE	HENRIES
L2	FILTER INDUCTANCE	HENRIES
CO	FILTER CAPACITANCE	FARADS
PDR	PHASE DELAY RECTIFIER GAIN	-----
K1	CONTROL LOOP GAIN	-----
K2	CONTROL LOOP GAIN	-----
T1	CONTROL LOOP TIME CONSTANT	SECS
T2	CONTROL LOOP TIME CONSTANT	SECS

OUTPUTS

PHYSICAL QUANTITY NAME	DESCRIPTION	UNITS
VO *	GENERATOR OUTPUT VOLTAGE	VOLTS
ALO *	FILTER INDUCTOR CURRENT	AMPS
V2 *	CONTROL LOOP VOLTAGE	VOLTS
X3 *	INTERMEDIATE STATE / CONTROL LOOP	-----
V1	CONTROL LOOP ERROR VOLTAGE	VOLTS
V3	CONTROL LOOP VOLTAGE	VOLTS
LO	TOT GEN AND FILTER INDUCTANCE	HENRIES
ALT	TOTAL LOAD CURRENT	AMPS
VP	VOLTAGE OUT OF PDR	VOLTS

* State Variables

Figure 13 Generation System Component (G1) Input/Output List

```
CG1
      SUBROUTINE G1(VO,VODOT,IVO,ALO,ALODOT,IALO,X3,X3DOT,IX3,
     1 V2,V2DOT,IV2,V1,V3,LO,ALT,VP,
     2 AL,AL1,L1,L2,CO,PDR,K1,K2,T1,T2,VR,RO)
C
C     SOLID ROTOR GENERATION SYSTEM
C     WRITTEN BY D.SOMMER
C     LATEST REVISION 4/20/80
C
C                INPUT/OUTPUT LIST
C
C  SYMBOL            NAME                           UNIT      ELEMENT TYPE
C
C  VO     GENERATOR OUTPUT VOLTAGE                  VOLTS     OUTPUT STATE
C  ALO    FILTER INDUCTOR CURRENT                   AMPS      OUTPUT STATE
C  V2     CONTROL LOOP VOLTAGE                      VOLTS     OUTPUT STATE
C  X3     INTERMEDIATE STATE / CONTROL LOOP         ----      OUTPUT STATE
C
C  V1     CONTROL LOOP ERROR VOLTAGE                VOLTS     OUTPUT VARIABLE
C  V3     CONTROL LOOP VOLTAGE                      VOLTS     OUTPUT VARIABLE
C  LO     TOT GEN AND FILTER INDUCTANCE             HENRIES   OUTPUT VARIABLE
C  ALT    TOTAL LOAD CURRENT                        AMPS      OUTPUT VARIABLE
C  VP     VOLTAGE OUT OF PDR                        VOLTS     OUTPUT VARIABLE
C
C  AL     LOAD CURRENT                              AMPS      INPUT  VARIABLE
C  AL1    LOAD CURRENT (CONTINUOUS)                 AMPS      INPUT  VARIABLE
C
C  VR     VOLTAGE REFERENCE                         VOLTS     INPUT  PARAMETER
C  L1     GENERATOR INDUCTANCE                      HENRIES   INPUT  PARAMETER
C  L2     FILTER INDUCTANCE                         HENRIES   INPUT  PARAMETER
C  RO     EFFECTIVE INDUCTOR RESISTANCE             OHMS      INPUT PARAMETER
C  CO     FILTER CAPACITANCE                        FARADS    INPUT  PARAMETER
C  PDR    PHASE DELAY RECTIFIER GAIN                ----      INPUT  PARAMETER
C  K1     CONTROL LOOP GAIN                         ----      INPUT  PARAMETER
C  K2     CONTROL LOOP GAIN                         ----      INPUT  PARAMETER
C  T1     CONTROL LOOP TIME CONSTANT                SECS      INPUT  PARAMETER
C  T2     CONTROL LOOP TIME CONSTANT                SECS      INPUT  PARAMETER
C
      REAL K1,K2,LO,L1,L2
C  CALCULATE TOTAL LOAD CURRENT
      ALT=AL+AL1
C  CALCULATE TOTAL OUTPUT INDUCTANCE
      LO=L1+L2
C  CALCULATE REGULATOR ERROR VOLTAGE
      V1=VR-VO
C  CALCULATE VOLTAGE V3
      V3=(V2*K2*T1+X3)/T2
C  CALCULATE VOLTAGE GAIN THRU PDR
      VP=V3*PDR
C  COMPUTE SYSTEM STATE EQUATIONS
      IF(IVO.NE.0)   VODOT=(ALO-ALT)/CO
      IF(IV2.NE.0)   V2DOT=K1*V1
      IF(IALO.NE.0)  ALODOT=(VP-ALO*RO-VO)/LO
      IF(IX3.NE.0)   X3DOT=V2*K2-V3
      RETURN
      END
```

Figure 14 Generation System Component (G1) Subroutine Listing

Required Inputs of the G1 Component

The G1 component requires the following input parameters which represent system data either available directly from the vendors or calculated from vendor data. VR is the generator regulator system reference voltage. L1 is the generator inductance and L2 is the output filter inductance. RO is the effective resistance of the system inductors. The stability of the G1 component is highly sensitive to this resistance value, due largely to the small inductive and capacitive values in the output filter. CO is the output filter capacitance value. The component gain constants, as computed in reference 3 include PDR, the phase delay rectifier gain; K1 the control loop gain; and K2, a second control loop gain. The control loop time constants are T1 and T2.

Variable inputs required by the G1 component are AL and AL1. The system load currents which simulate a dual parallel channel input. These component variables are required as parameter values for single component analysis or as variable inputs when interfaced with other components during system analysis.

Computed Outputs of the G1 Component

There are four computed state variables for the G1 component. As seen in the subroutine listing of this component (figure 14), the derivatives of the state variables are designated by the suffix "DOT". The state VO is the rectified DC voltage across the output filter capacitor. This voltage is also used as the P.O.R. for our model. The state V2 represents the control loop voltage as generated by the control loop integrator (figure 12). The state X3 represents the lead-lag function of the generator/regulator control loop. The fourth state ALO is the current through the output filter inductor.

Output variables include V1 the control loop error voltage. In the G1 component representation of the solid rotor machine the error voltage V1 is the difference between the reference voltage and the generation system output voltage, used as the P.O.R. The variable V3, the control loop voltage, is computed from the error voltage and lead-lag function voltages. The variable LO represents the total generation system inductance values. The output variable ALT is the total load current representation. Lastly, the variable VP represents the rectified DC voltage from the phase delay rectifiers.

2.5 FLAT CONDUCTOR FEEDER BUS COMPONENT

Flat conductor feeder bus distribution systems are being considered for solving distribution problems imposed by composite structures, high voltage DC power sources and solid state control components. In particular, a multiple flat conductor distribution system for a high voltage 270 VDC aircraft power system is desirable for the reduced weight and its characteristics of reduced inductance and increased capacitance (reference 19).

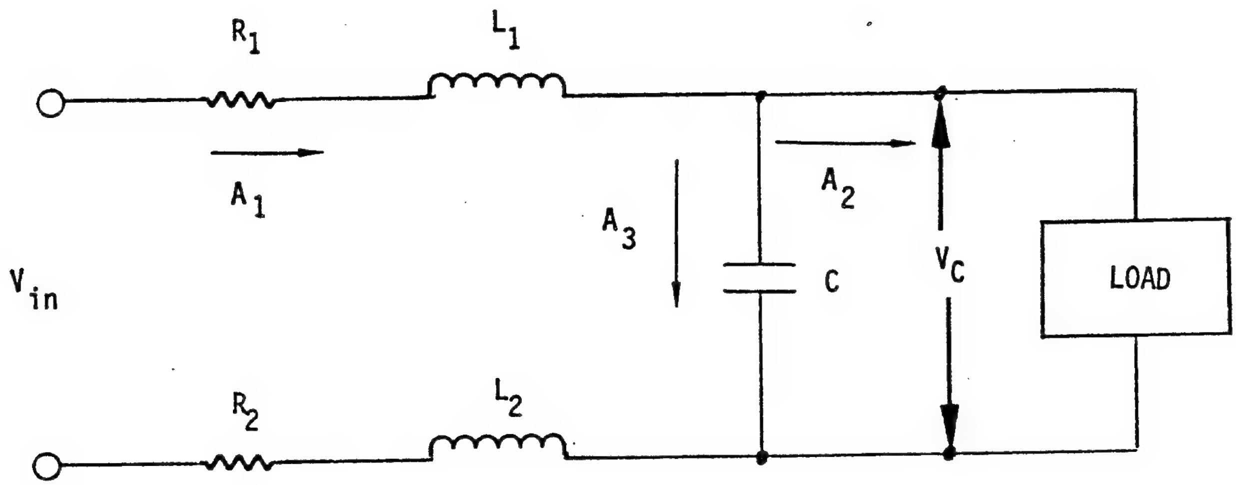
The flat conductor bus system consists of a pair of flat conductor cables separated by a dielectric. These flat conductor cables are electrically similar to circular conductor cables for computer modelling purposes (reference 20). The computer model, however, reflects the lower reactance and higher capacitance characteristics of the flat conductors by considering wire dimensions and wire resistivity and dielectric constants in the computation of system time varying elements. The wire parameter values can be easily changed in the model to simulate any type or size system.

2.5.1 Formulation of Equations

The flat conductor feeder bus shown in figure 15 has two state variables which are defined as follows: The feeder current I_L through its lumped inductance; and the feeder voltage V_C dropped across its lumped capacitance. The following state equations can be derived from the schematic representation of the flat conductor feeder bus shown in the figure.

Flat Conductor Feeder Current:

$$\frac{dI_L}{dt} = \frac{V_{IN} - I_L\,(R_1 + R_2) - V_C}{L_1 + L_2} \qquad (22)$$



EQUATIONS:

$$\frac{dA_1}{dt} = (V_{in} - A_1 (R_1 + R_2) - V_C)/(L_1 + L_2)$$

$$\frac{dV_C}{dt} = A_3 / C$$

$$A_3 = A_1 - A_2$$

Figure 15 Flat Conductor Feeder Schematic

Flat Conductor Feeder Voltage:

$$\frac{dV_C}{dt} = \frac{I_C}{T_C} \tag{23}$$

(Where T_C represents the total capacitance of the flat conductor feeder, L_1 and L_2 represent the flat conductor feeder inductances and R_1 and R_2 represent the resistances).

Flat Conductor Capacitance:

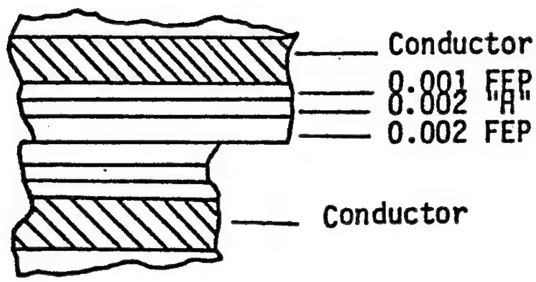
$$T_C = \frac{C_P\ C_S}{C_P + C_S} \tag{24}$$

The flat two conductor feeder is physically represented as shown in figure 16. This cross-section of adjacent flat conductor feeders shows an insulation system. The total thicknesses of insulation between the two adjacent conductors is used to calculate the capacitance between feeders.

Thus, where

C = Capacitance
E_0 = Permittivity
H = Thickness of Dielectric
A = Area of Conductor

$$C = \frac{E_0\ A}{H} \tag{25}$$



The cross-section of adjacent FCC feeders above shows the insulation system. The total thicknesses of insulation between the two adjacent conductors is used to calculate the capacitance between feeders.

Thus, where

C = Capacitance, farads

E_0 = Permittivity, farads/meter

h = thickness of dielectric, in.

$$C = \frac{E_0 A}{h}$$

Figure 16 Physical System Representation of Flat Conductor Feeder

Then from figure 16 where C_P is the capacitance of the primary dielectric and C_S is the capacitance of the secondary dielectric:

$$C_P = \frac{P_D \; E_0 \; W_W}{P_{DT}} \tag{26}$$

$$C_S = \frac{S_D \; E_0 \; W_W}{S_{DT}} \tag{27}$$

Defining the parameters used to calculate these capacitance values;

- P_D is the primary dielectric constant
- P_{DT} is the primary dielectric thickness
- S_D is the secondary dielectric constant
- S_{DT} is the secondary dielectric thickness
- E_0 is the conductor premittivity constant
- W_W is the conductor width

These equations formulate the flat conductor feeder bus model we have used for the HVDC system. All states, variables, and parameters of the flat conductor feeder bus model are defined in the input/output listing shown in figure 17.

2.5.2 EASY Standard Component, FC

FC is the EASY standard component representation of the flat conductor feeder bus model. The FC component is a Fortran subroutine that meets the specific requirements of the EASY program as defined in reference 2. The EASY standard component subroutine listing of the flat conductor feeder bus is shown in

FLAT CONDUCTOR CABLE

INPUTS

L1	CONDUCTOR INDUCTANCE (SENDING)	HENRIES/1K FT
L2	CONDUCTOR INDUCTANCE (RETURN)	HENRIES/1K FT
AL	LOAD CURRENT	AMPS
AL1	LOAD CURRENT (CONTINUOUS)	AMPS
VIN	INPUT VOLTAGE	VOLTS
EO	PERMITTIVITY CONSTANT	FARADS/METER
WW	CONDUCTOR WIDTH	INCHES
WL	CONDUCTOR LENGTH	FEET
WT	CONDUCTOR THICKNESS	INCHES
PD	PRIMARY DIELECTRIC CONSTANT	
PDT	PRIMARY DIELECTRIC THICKNESS	INCHES
SD	SECONDARY DIELECTRIC CONSTANT	
SDT	SECONDARY DIELECTRIC THICKNESS	INCHES
RO	CONDUCTOR RESISTIVITY	OHMS-SQ.FT/FT
MF	CONVERSION CONSTANT (METERS-1K FT.)	DECIMAL
SF	CONVERSION CONSTANT (SQ.IN.-SQ.FT.)	INTEGER

OUTPUTS

IL *	SOURCE CURRENT THROUGH INDUCTOR	AMPS
ILDOT	DERIVATIVE OF IL	
VC *	CAPACITOR VOLTAGE PARALLELING LOAD	VOLTS
VCDOT	DERIVATIVE OF VC	
CP	CAPACITANCE-PRIMARY DIELECTRIC	FARADS/METER
CS	CAPACITANCE-SECONDARY DIELECTRIC	FARADS/METER
TC	TOTAL CAPACITANCE	FARADS/METER
TC1	TOTAL CAPACITANCE	FARADS/1K FT.
R1	CONDUCTOR RESISTANCE (SENDING)	OHMS
R2	CONDUCTOR RESISTANCE (RETURN)	OHMS
AX	CROSS-SECTIONAL AREA OF CONDUCTORS	SQUARE FEET
I2	TOTAL LOAD CURRENT (AL+AL1)	AMPS

* State Variables

Figure 17 Flat Conductor Feeder Component (FC) Input/Output List

figure 18. All symbols used in the component are defined in the subroutine listing and the input/output listing and specifically described below as they relate to the schematic of the flat conductor feeder bus shown in figure 15.

Required Inputs of the FC Component

The FC component requires the following input parameters which represent flat conductor configuration specifications and conversion constants. WW is the flat conductor width specified in inches. WL is the flat conductor length specified in feet. WT is the flat condutor thickness specified in inches. Conversion constants required are MF, which converts meters to feet and SF, which converts square inches to square feet. Typical conductor insulation characteristics required are specified by PD, the primary dielectric constant; PDT, the primary dielectric thickness; SD, the secondary dielectric constant; and SDT, the secondary dielectric thickness. Other electrical characteristics required are E0, the permittivity constant and R0, the resistivity of the conductor. Also required as part of the electrical description of the feeder are the inductance values L1 and L2. For the greatest flexibility in analyzing the system, these values are user inputs rather than calculated in the component itself.

Variable inputs required by the FC component are VIN, the feeder input voltage; and AL and AL1 the currents demanded by the loads from the feeder. The component input variables are required as parameters for single component stand alone analysis or as variable inputs interfaced with other components during system analysis as specified in the EASY model generation program.

Computed Outputs of the FC Component

There are two computed state variables for the FC component. The first, IL, is the source current through the lumped inductor representation of the flat conductor feeder model. The second state, VC, is the voltage developed across the lumped capacitance of the conductor representation. The derivatives of the current and voltage are ILDOT and VCDOT respectively as shown in the subroutine listing of the FC component (figure 18).

```
CFC
C
      SUBROUTINE FC(IL,ILDOT,IIL,VC,VCDOT,IVC,CP,CS,TC,TC1,R1,R2,AX,I2,
     1 L1,L2,VIN,EO,WW,WL,WT,PD,PDT,SD,SDT,RO,MF,SF,AL,AL1)
C
C     WRITTEN BY D.SOMMER
C     FLAT CABLE CONDUCTOR MODEL
C     LATEST REVISION 2/7/80
C
C                INPUT/OUTPUT LIST
C
C  SYMBOL    NAME                                UNIT            ELEMENT TYP
C
C  IL     SOURCE CURRENT THROUGH INDUCTOR        AMPS            OUTPUT STATE
C  ILDOT  DERIVATIVE OF IL
C  VC     CAPACITOR VOLTAGE PARALLELING LOAD     VOLTS           OUTPUT STA
C  VCDOT  DERIVATIVE OF VC
C  CP     CAPACITANCE-PRIMARY DIELECTRIC         FARADS/METER    OUTPUT VARIABL
C  CS     CAPACITANCE-SECONDARY DIELECTRIC       FARADS/METER    OUTPUT VAR
C  TC     TOTAL CAPACITANCE PER METER            FARADS/METER    OUTPUT VARI
C  TC1    TOTAL CAPACITANCE                      FARADS          OUTPUT VARIABL
C  R1     CONDUCTOR RESISTANCE (SENDING)         OHMS            OUTPUT VAR
C  R2     CONDUCTOR RESISTANCE (RETURN)          OHMS            OUTPUT VAR
C  AX     CROSS-SECTIONAL AREA OF CONDUCTORS     SQUARE FEET     OUTPUT VARIABL
C  I2     TOTAL LOAD CURRENT (AL+AL1)            AMPS            OUTPUT VARI
C  L1     CONDUCTOR INDUCTANCE (SENDING)         HENRIES/1K FT   INPUT VARI
C  L2     CONDUCTOR INDUCTANCE (RETURN)          HENRIES/1K FT   INPUT VARIABLE
C  AL     LOAD CURRENT                           AMPS            INPUT  VARIABL
C  AL1    LOAD CURRENT (CONTINUOUS)              AMPS            INPUT
C  VIN    INPUT VOLTAGE                          VOLTS           INPUT  VARI
C  EO     PERMITTIVITY CONSTANT                  FARADS/METER    INPUT  PARAMET
C  WW     CONDUCTOR WIDTH                        INCHES          INPUT  PARA
C  WL     CONDUCTOR LENGTH                       FEET            INPUT  PARA
C  WT     CONDUCTOR THICKNESS                    INCHES          INPUT  PARAMET
C  PD     PRIMARY DIELECTRIC CONSTANT                            INPUT  PARAMET
C  PDT    PRIMARY DIELECTRIC THICKNESS           INCHES          INPUT  PARA
C  SD     SECONDARY DIELECTRIC CONSTANT                          INPUT  PARA
C  SDT    SECONDARY DIELECTRIC THICKNESS         INCHES          INPUT  PARAMET
C  RO     CONDUCTOR RESISTIVITY                  OHMS-SQ.FT/FT   INPUT  PARA
C  MF     CONVERSION CONSTANT (METERS-FT.)       DECIMAL         INPUT  PARA
C  SF     CONVERSION CONSTANT (SQ.IN.-SQ.FT.)    INTEGER         INPUT  PARAMET
      REAL I2,IC,IL,ILDOT,L1,L2,MF
C  COMPUTE FLAT CONDUCTOR CABLE VARIABLES
      I2=AL+AL1
      CP=PD*EO*WW/PDT
      CS=SD*EO*WW/SDT
      TC=CP*CS/(CP+CS)
      TC1=TC*MF*WL
      AX=WW*WT/SF
      R1=RO*WL/AX
      R2=R1
C  CALCULATE STATE VARIABLES
      ILDOT=(VIN-IL*(R1+R2)-VC)/(L1+L2)
      VCDOT=(IL-I2)/TC1
      IF(IIL.EQ.0.0) ILDOT=0.0
      IF(IVC.EQ.0.0) VCDOT=0.0

      RETURN
      END
```

Figure 18 Flat Conductor Feeder Component (FC) Subroutine Listing

Output variables include CP, the capacitance of the primary dielectric (i.e., Teflon), and CS, the capacitance of the secondary dielectric (i.e., Kapton) as depicted in figure 16. The variable TC is the combined capacitance of the dielectrics CS and CP per unit length while TC1 is the total capacitance of the flat conductor being analyzed. The flat two-conductor resistance values R1 (power) and R2 (return) are considered to be equal and are computed from the conductor cross sectional area AX (also a computed output), the conductor length WL and the resistivity RO. The total load current, I2, represents the total load demand in amps and is the sum of the variables AL and AL1.

2.6 LOAD COMPONENTS

There are several types of loads that create power quality problems for future electrical power systems. An analytical tool which helps define these problems for advance systems will ensure the development of reliable power for the essential aircraft loads. One technique is the development of computer models for analysis by the EASY digital computer program. The load models prepared for this type of analysis are described below.

2.6.1 RLC Load Component

The RLC load model as shown in figure 19 is representative of many loads on the aircraft. The resistive parameter R_L, the inductive parameter L_0, and the capacitive parameter C_0, can be varied to check for any instabilities that may be caused anywhere in the power and distribution system. The EASY model can be used to represent cyclic, pulsed or continuous loads.

2.6.1.1 Formulation of Equations

The RLC load model as shown in figure 19 has two states which are defined as follows: the voltage across the load capacitor, V_C, and the current through the load inductor A_1. The following equations are then derived from the load schematic.

Capacitor Voltage:

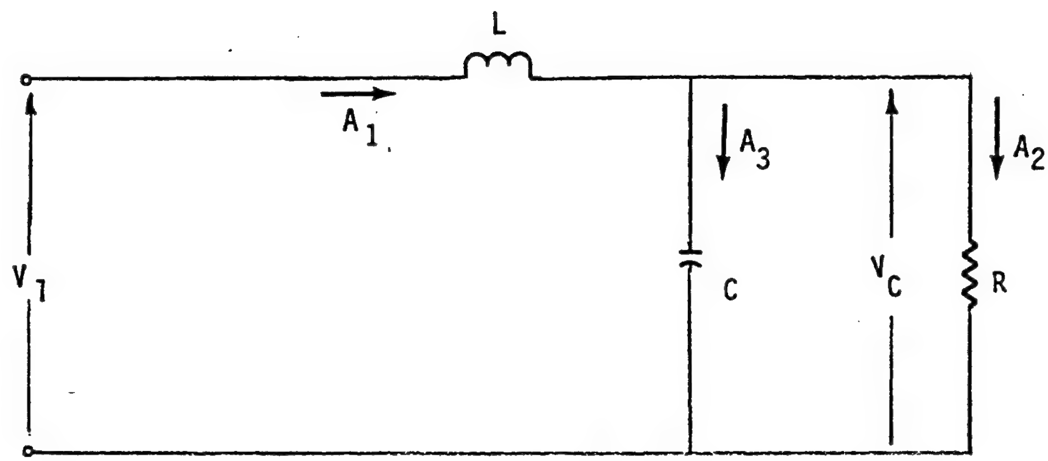
$$\frac{dV_C}{dt} = (A_1 - A_2) \frac{1}{L_0} \tag{28}$$

where A_2 is the current through the load resistance.

Inductor Current:

$$\frac{dA_1}{dt} = (V_1 - A_1 R_0 - V_C) \frac{1}{L_0} \tag{29}$$

where R_0 is the effective inductor resistance and V_1 is the input voltage provided by the power source.



Describing Equations:

$$\frac{dA_1}{dt} = (V_1 - V_C)/L$$

$$\frac{dV_C}{dt} = (A_1 - V_C/R)/C$$

Figure 19 RLC Load Schematic

All states, variables and parameters of the RLC load model are defined in the input/output listing shown in figure 20.

2.6.1.2 EASY Standard Component, L6

L6 is the EASY standard component representation of the RLC load model. The L6 component is a Fortran subroutine that meets the specific requirements of the EASY program and like all EASY standard components is stored in the component library.

The L6 standard component subroutine listing is shown in figure 21. All symbols used in the component are defined in the subroutine listing and the input/output listing.

Required Inputs of the L6 Component

The L6 component requires the following input parameters which represent load data that are determined by the user for specific system applications. L0 is the inductance value for the load inductor and R0 is its effective resistance. C0 is the capacitance value for the load capacitor. RL is the resistive load as seen by the source. The only variable input required by the L6 component is V1 which represents the source voltage at the load terminals. This variable is required as a parameter value for single component analysis or as a variable input when interfaced with other components during system simulations.

Computed Outputs of the L6 Component

The L6 component computes two state variables, A1, the current through the load inductor, and VC, the voltage developed across the load capacitor. The state derivatives of the component are designated by "DOT" as can be seen in the subroutine listing (figure 21). The only variable computed is A2, the current through the load resistor, RL.

L6

RLC LOAD

INPUTS

LO	LOAD INDUCTANCE	HENRIES
RO	INDUCTOR RESISTANCE	OHMS
CO	LOAD CAPACITANCE	FARADS
RL	LOAD RESISTANCE	OHMS
V1	RLC NETWORK INPUT VOLTAGE	VOLTS

OUTPUTS

A1*	LOAD INDUCTOR CURRENT	AMPS
VC*	LOAD CAPACITOR VOLTAGE	VOLTS
A2	CURRENT THROUGH LOAD	AMPS

* STATE VARIABLES

Figure 20 RLC Load Component (L6) Input/Output List

```
CL6
      SUBROUTINE L6(A1,A1DOT,IA1,VC,VCDOT,IVC,
     1 A2,V1,LO,CO,RL,RO)
C
C     RLC LOAD CIRCUIT MODEL
C     WRITTEN BY D.SOMMER
C     LATEST REVISION 6-15-80
C
C              INPUT / OUTPUT LIST
C
C  SYMBOL           NAME                          UNIT     ELEMENT TYPE
C
C  A1       LOAD INDUCTOR CURRENT                 AMPS     OUTPUT STATE
C  VC       LOAD CAPACITOR VOLTAGE                VOLTS    OUTPUT STATE
C
C  A2       CURRENT THRU LOAD                     AMPS     OUTPUT VARIABLE
C
C  V1       RLC NETWORK INPUT VOLTAGE             VOLTS    INPUT VARIABLE
C
C  LO       LOAD INDUCTANCE                       HENRIES  INPUT PARAMETER
C  RO       INDUCTOR RESISTANCE                   OHMS     INPUT PARAMETER
C  CO       LOAD CAPACITANCE                      FARADS   INPUT PARAMETER
C  RL       LOAD RESISTANCE                       OHMS     INPUT PARAMETER
C
      REAL LO
C  CALCULATE LOAD CURRENT
      A2=VC/RL
C  CALCULATE SYSTEM STATE EQUATIONS
      IF (IA1.NE.0)  A1DOT=(V1-A1*RO-VC)/LO
      IF (IVC.NE.0)  VCDOT=(A1-A2)/CO
      RETURN
      END
```

Figure 21 RLC Load Component (L6) Subroutine Listing

2.6.2 Lighting Load Component

The lighting load model is representative of the lighting circuits aboard the aircraft. Large lighting loads when initially turned on may cause unwanted line perturbations and may then effect the stability of the power system, especially when switching type power supplies are used. Lighting loads have the characteristic of a high inrush current that is caused by the lower resistances associated with the cold lighting filaments.

2.6.2.1 Formulation of Equations

The lighting load model, as shown in figure 22 with its inrush current characteristic curve, has one state variable. A1 is the current through the inductive element L_0, of the model which develops the instantaneous load voltage across the time varying load resistance, R_0, of the lighting filaments.
The state equation for the inductor current is,

$$\frac{dA_1}{dt} = (V_1 - A_1 R_0) \frac{1}{L_0} \qquad (30)$$

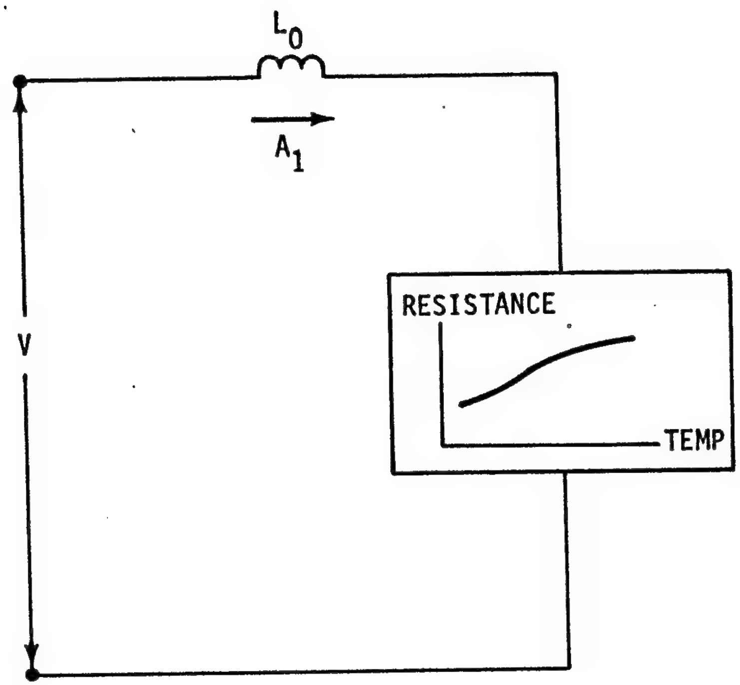
where V_1 is the input voltage provided by the power source.

All states, variables and parameters of the lighting load model are defined in the input/output listing shown in figure 23.

2.6.2.2 EASY Standard Component, L7

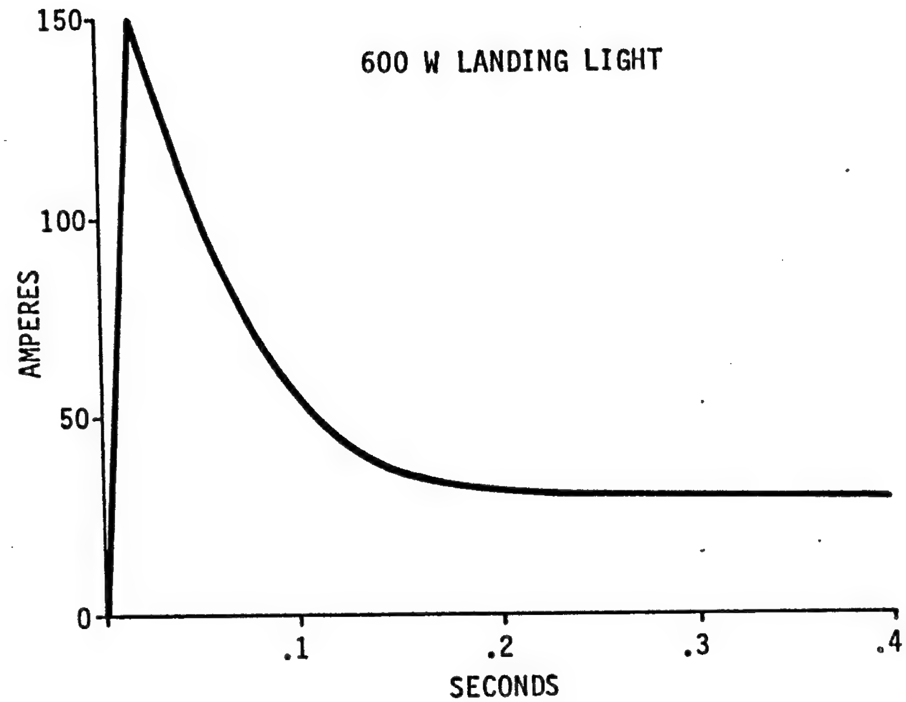
L7 is the EASY standard component representation of the lighting load model. The L7 component is a Fortran subroutine that meets the specific requirements of the EASY program.

The L7 component subroutine listing is shown in figure 24. All symbols used in the component are defined in the subroutine listing and input/output listing.



DESCRIBING EQUATION: $\frac{dA_1}{dt} = (V - A_1 R_{(TEMP)})/L_0$

EQUIVALENT CIRCUIT



INRUSH CURRENT CHARACTERISTIC

Figure 22 Lighting Load Schematic

LIGHTING LOAD

INPUTS

LO	LOAD INDUCTANCE	HENRIES
AM	DEGREE OF INTERPOLATION FOR TABLE AVT	-------
AVT	TABLE: LIGHTING INRUSH CURRENT FUNCTION	-------
V1	LIGHTING LOAD INPUT VOLTAGE	VOLTAGE

OUTPUTS

A1*	LOAD INDUCTOR CURRENT	AMPS
RO	LOAD RESISTANCE	

* STATE VARIABLES

Figure 23 Lighting Load Component (L7) Input/Output List

```
CL7
      SUBROUTINE L7(AVT,A1,A1DOT,IA1,RO,V1,LO,AM)
C
C     LIGHTING LOAD CIRCUIT MODEL
C     WRITTEN BY U.SOMMER
C     LATEST REVISION 6-15-80
C
C             INPUT / OUTPUT  LIST
C
C  SYMBOL          NAME                             UNIT     ELEMENT TYPE
C
C  AVT       LIGHTING INRUSH CURRENT/RESISTANCE              INPUT TABLE
C            MAXIMUM DATA POINTS = 16
C
C  A1        LOAD INDUCTOR CURRENT                  AMPS     OUTPUT STATE
C
C  RO        LOAD RESISTANCE                        OHMS     OUTPUT VARIABL
C
C  V1        LIGHTING LOAD INPUT VOLTAGE            VOLTS    INPUT VARIABLE
C
C  LO        LOAD INDUCTANCE                        HENRIES  INPUT PARAMETE
C  AM        DEGREE OF INTERPOLATION-TABLE AVT               INPUT PARAMETE
C            NEGATIVE VALUE WILL PREVENT
C            INTERPOLATION BEYOND TABLE LIMITS
C
      DIMENSION AVT(1)
      COMMON/CTIME/TIME
      REAL LO
      MA=AVT(2)*AM/ABS(AM)
      MB=AVT(2)+4
      M=ABS(AM)
C  CALCULATE LOAD RESISTANCE
      RO=TBLU1(TIME,AVT(4),AVT(MB),M,MA)
C  CALCULATE COMPONENT STATE VARIABLE
      A1DOT=(V1-A1*RO)/LO
      RETURN
      END
```

Figure 24 Lighting Load Component (L7) Subroutine Listing

Required Inputs of the L7 Component

The L7 component requires table look-up data to establish the inrush current function similar to that shown in figure 22. This information is transmitted to the L7 subroutine via the EASY program as specified within the subroutine. The table is designated as AVT.

Additionally, the L7 component requires the input parameter, LO, which represents load inductance that is determined by the user for specific system applications. The parameter AM is used by the table routine to determine the degree of interpolation. A negative value specified by the user will prevent interpolation beyond the table limits. The only variable input required by the L7 component is V1 which represents the source voltage at the load terminals. This variable is required as a parameter value for single component analysis or as a variable input when interfaced with other components during system simulations.

Computed Outputs of the L6 Component

The L7 component computes one state variable, A1, which represents the current through the load inductor. The state derivative is designated by "DOT" as can be seen in the subroutine listing (figure 24). RO is the output computed from the table look-up data. Additional variables MA, MB, and M are used by the table look-up routine for interpolation limiting.

SECTION III

HVDC SYSTEM MODEL SIMULATIONS

Simulation examples of the HVDC Electrical System Components in four configurations are described and detailed in this section. All simulations of the system models are accomplished on the EASY program. Each system configuration or model must be defined in the EASY model generation file and the analysis to be performed on that model must be defined in the EASY analysis file (reference 1 and 2). These files, submitted to the EASY program, provide the means by which we can analyze the systems.

Each component as defined in Section II can be modelled on the EASY program as an independent system. This allows the EASY analysis to be performed on each component to determine its stability and dynamic response characteristics prior to complete system or multiple component analysis. For comparison purposes, the following simulations were conducted to show the versatility of the components and to demonstrate some of the capabilities of the EASY program.

3.1 BUCK SWITCHING REGULATOR WITH LOAD

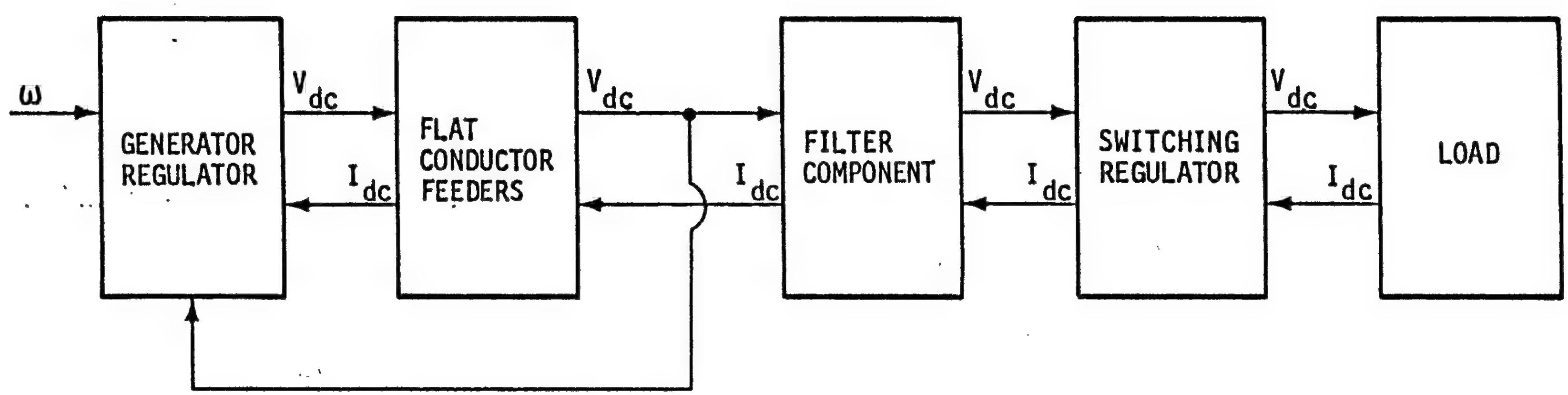
The buck switching regulator component S4, is shown in figure 25 interconnected with a load component. Two simulations were conducted on the two component system; the first is with the L6, RLC load component, and the second with the L7, lighting load component. All simulation procedures are documented in detail in the EASY user's manuals (reference 1 and 2).

3.1.1 Switching Regulator with RLC Load

The dynamic simulation of the switching regulator with load is accomplished in the following manner.

To generate a dynamic simulation the model must be defined, the required components must be determined, and the system operating point must be specified. The EASY model generation and analysis files for the first model which consists of the switching regulator component, S4, and the RLC load component, L6, are shown in figures 26 and 27 respectively. The model generation file describes the interconnection between the model components. This file, when submitted to the EASY program, generates the computer print out also shown in figure 26. Any errors in the model would be included in this print out. In this case the model is simple (only two components), however, for large systems this print out is quite useful and ensures correct model configuration.

The analysis file specifies the parameter values that each component requires, which are defined in the input/output list for each component. The operating point data specified includes the initial conditions for each state variable in the model and integration and error controls for each state as well. The analysis file also specifies the types of analyses to be performed. In this case a simulation of the model is requested for a time period of .5 milliseconds, this is to let the turn on transients die out. At this time in the simulation the load series resistance is changed to increase the load demand from 2 amperes to 10 amperes. The effect of the turn-on transient and the load change on selected variables of the model are shown in figures 28



<u>GEN/REG:</u>

3 2 VDC WOUND ROTOR GENERATOR/REGULATION LOOP

270 VDC SOLID ROTOR GENERATOR/REGULATOR LOOP

<u>FEEDER:</u>

TWO CONDUCTOR FLAT POWER

DISTRIBUTION BUS

<u>FILTER:</u>

TWO STAGE INPUT EMI

FILTER FOR SWITCHING REG.

<u>SWITCHING REG:</u>

MULTIPLE CONTROL LOOP

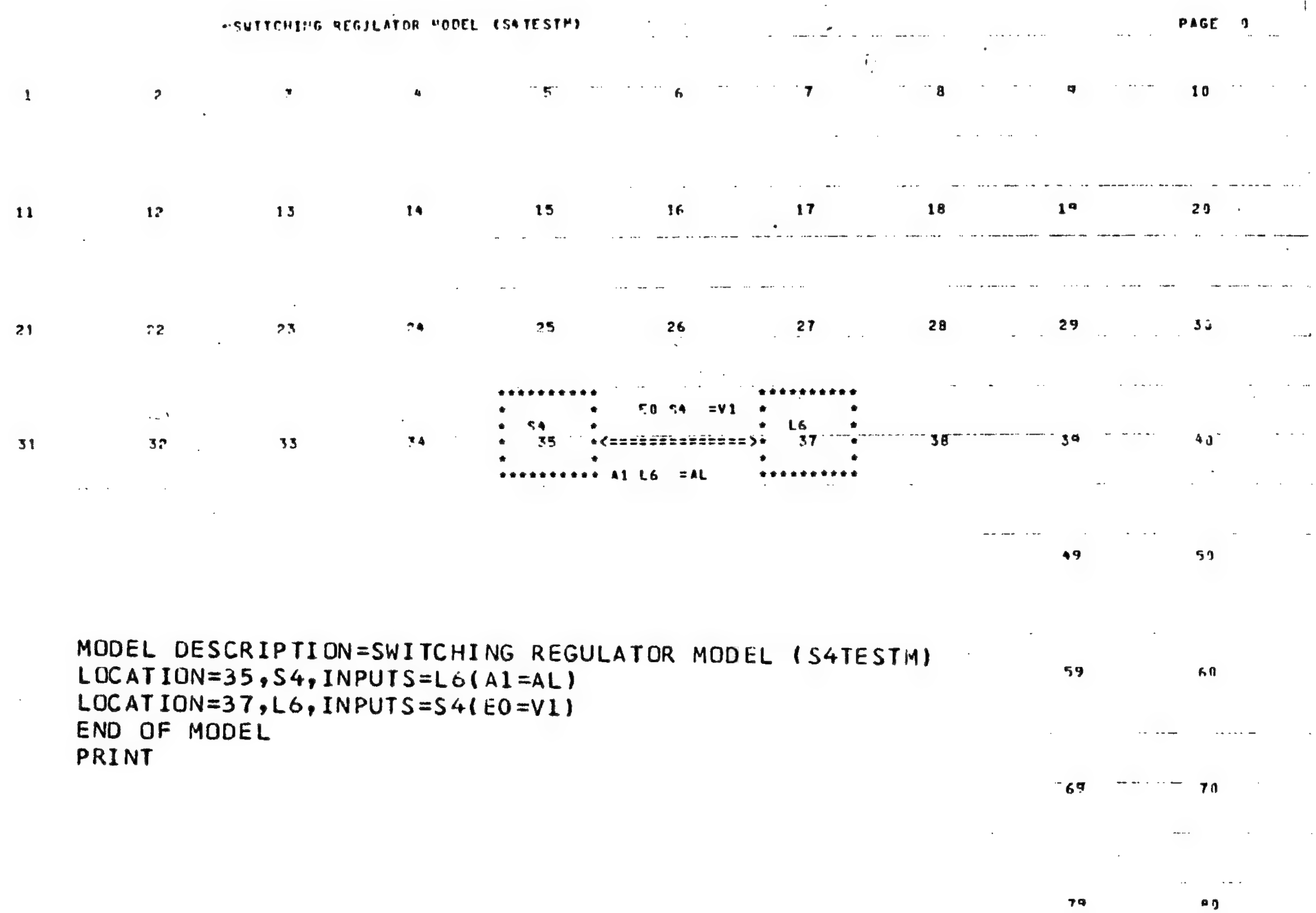
BUCK SWITCHING REGULATOR

LOAD:

ELECTRICAL RLC NETWORK

LIGHTING CIRCUIT

Figure 25 Switching Regulator with Load Block Diagram




```
MODEL DESCRIPTION=SWITCHING REGULATOR MODEL (S4TESTM)
LOCATION=35,S4,INPUTS=L6(A1=AL)
LOCATION=37,L6,INPUTS=S4(E0=V1)
END OF MODEL
PRINT
```

Figure 26 EASY Model Generation File and Model Schematic for Switching Regulator with RLC Load.

```
TITLE=SWITCHING REGULATOR MODEL WITH LOAD (S4TESTA)
PARAMETER VALUES
EI S4=30.0,ER S4=20.0,ET S4=8.0
R2 S4=13500,RO S4=.015,R1 S4=28700
R3 S4=10000,R4 S4=100000,R5 S4=.077
CO S4=.0003,C1 S4=.0022E-06,C2 S4=.022E-06
LO S4=.00025,N  S4=.065
TS S4=20E-06,TR S4=5E-06
RO L6=.015,LO L6=22E-06,CO L6=240E-06
RL L6=10.0
INITIAL CONDITIONS
XO S4=20.0
X1 S4=208,ALOS4=2.0
VC L6=20.0,A1 L6=2.0
ERROR CONTROLS
XO S4=.0001,X1 S4=.0001,ALOS4=.0001
VC L6=.0001,A1 L6=.0001
PRINT CONTROL=3
PRATE=2
OUTRATE=10
INT MODE=2
TMAX=.0005
TINC=1E-06
LINEAR ANALYSIS
PRINTER PLOTS
PLOT ON
SC4020
SI MANUAL SCALES
DISPLAY1
ALOS4,VS,TIME,YRANGE=0,30
EO S4,VS,TIME,YRANGE=15,25
EC S4,VS,TIME,YRANGE=0,50
DISPLAY2
VC L6,VS,TIME,YRANGE=15,25
A1 L6,VS,TIME,YRANGE=0,30
A2 L6,VS,TIME,YRANGE=0,30
SIMULATE
XIC-X
LINEAR ANALYSIS
INITIAL TIME=.0005
PARAMETER VALUES
RL L6=2.0
TMAX=.002
SIMULATE
XIC-X
LINEAR ANALYSIS
```

Figure 27 EASY Analysis File for Switching Regulator with RLC Load

through 31. Responses of the switching regulator variables to the turn on transient are shown in figure 28. As can be seen the voltage output EO, and the inductor current, ALO, recover to the average switching levels within a few microseconds. The load component voltage VC, and the load currents A1 and A2 as shown in figure 29, remain relatively constant over the time period simulated. The figures 30 and 31 display the same switching regulator and load variables for the time interval .5 milliseconds to 2 milliseconds which corresponds with the load change described above. The dynamic stability of the system is apparent in these figures and is also confirmed in the Linear Analysis as accomplished before and after the simulations by the EASY program. These Linear Analyses are shown in figure 32.

3.1.2 Switching Regulator with Lighting Load Model

Similar to the previous simulation, this model requires the model generation and analysis data for each of the components to be analyzed. The model is comprised of the S4 switching regulator component and the L7 lighting load component. The model generation and analysis files for the regulator and load model are shown in figures 33 and 34. The model generation schematic produced by the EASY program is also shown in figure 33 and shows the interconnections between the components as specified in the model generation file. The analysis file specifies the data requirements of the S4 component and the L7 component. These include the table data for the L7 component, and the parameter values, initial conditions, error controls, and types of analyses desired for the model.

The dynamic analysis of the model looks at the effect of a lighting type load on a switching regulator. The regulator is operating with a 30 volt input and a 20 volt output with a lighting load of about 400 watts. The variable inrush current characteristic of lighting loads are simulated with the table look up routine of the EASY program. The regulator inductor current, ALO, and output voltage, EO, dynamic response to the lighting load are shown in figure 35. The current A1 through the lighting load, and the lighting resistive load curve are shown in figure 36. A linear analysis of the model before and after the simulation as shown in figure 37 confirms the stability of the regulator with this type of loading.

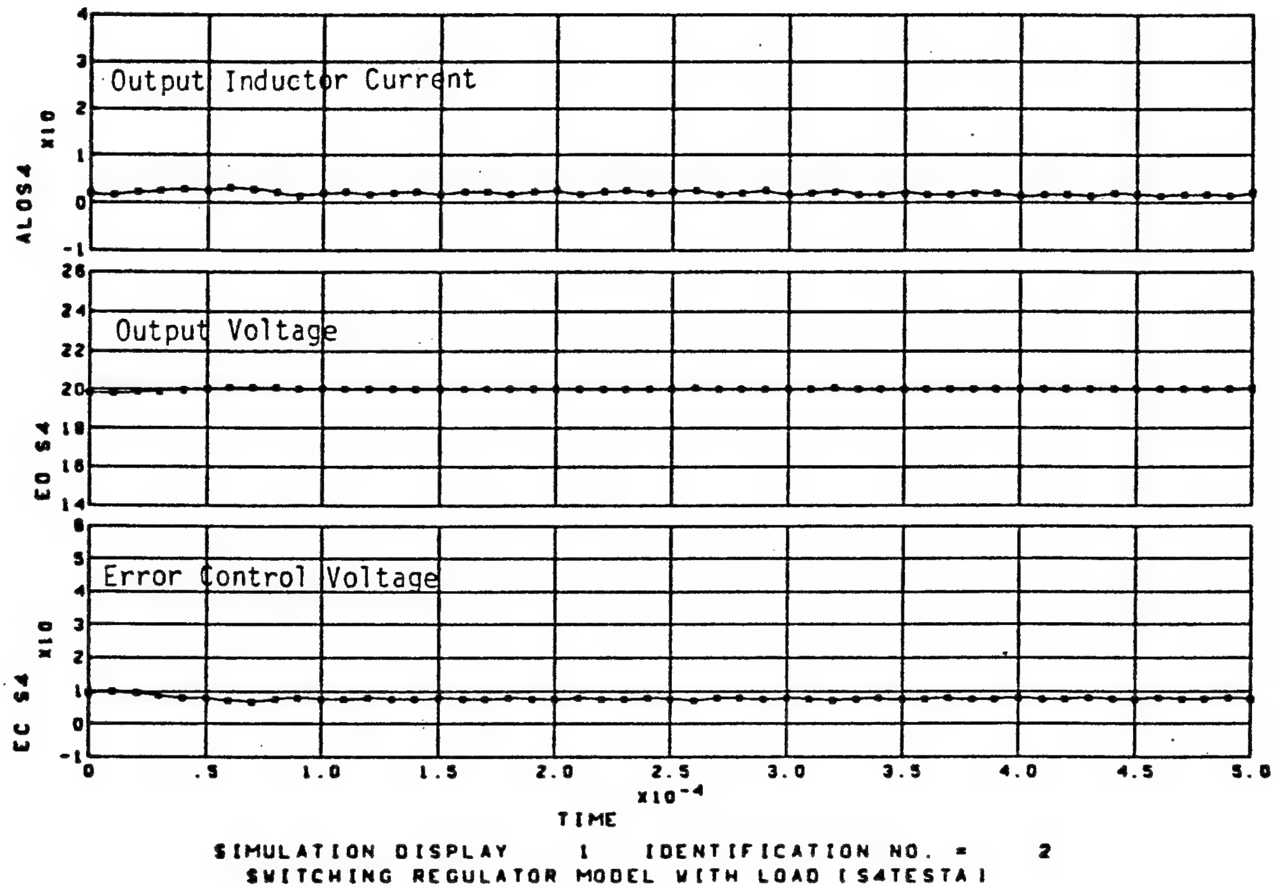


Figure 28 Transient Response (1a) of Switching Regulator with RLC Load

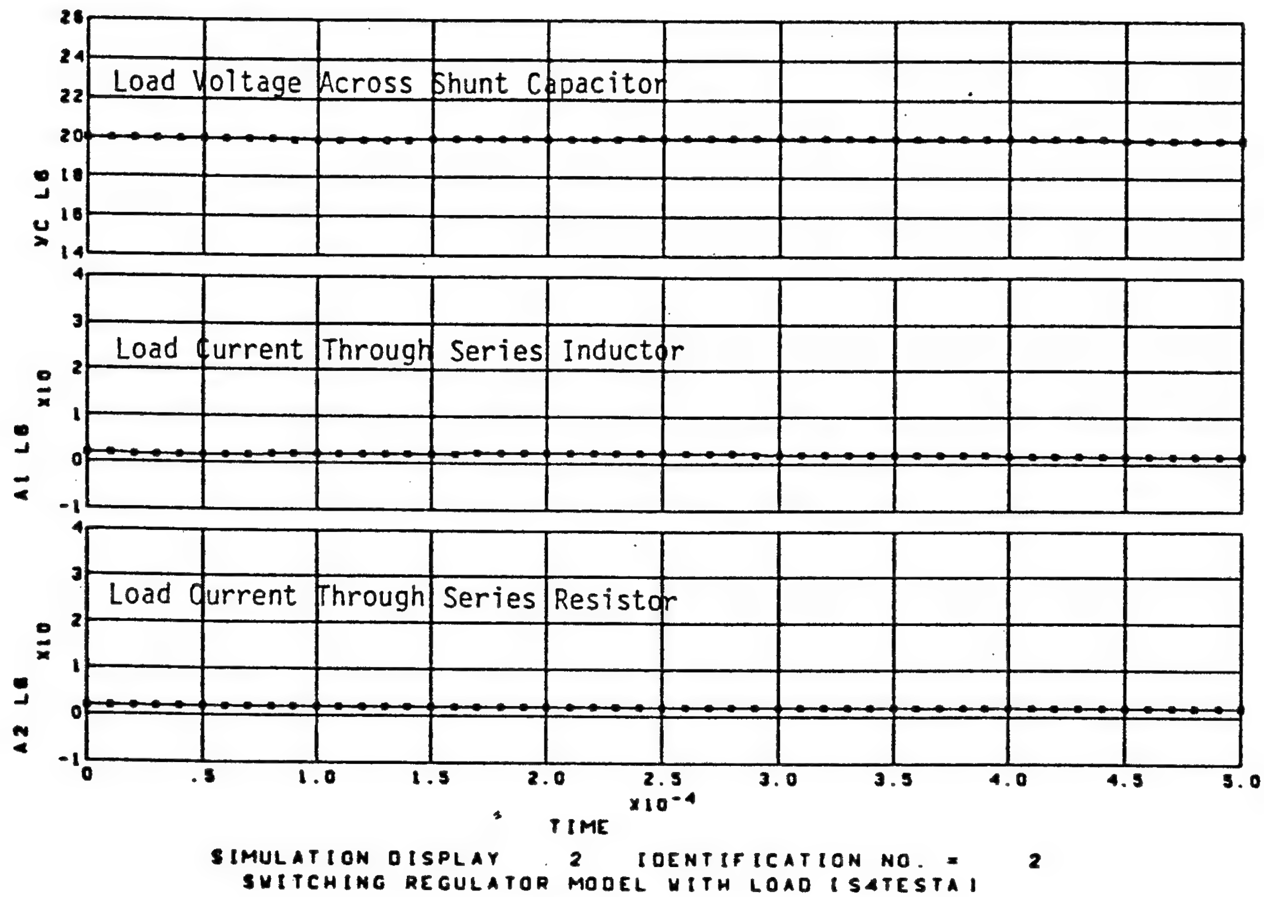


Figure 29 Transient Response (1b) of Switching Regulator with RLC Load

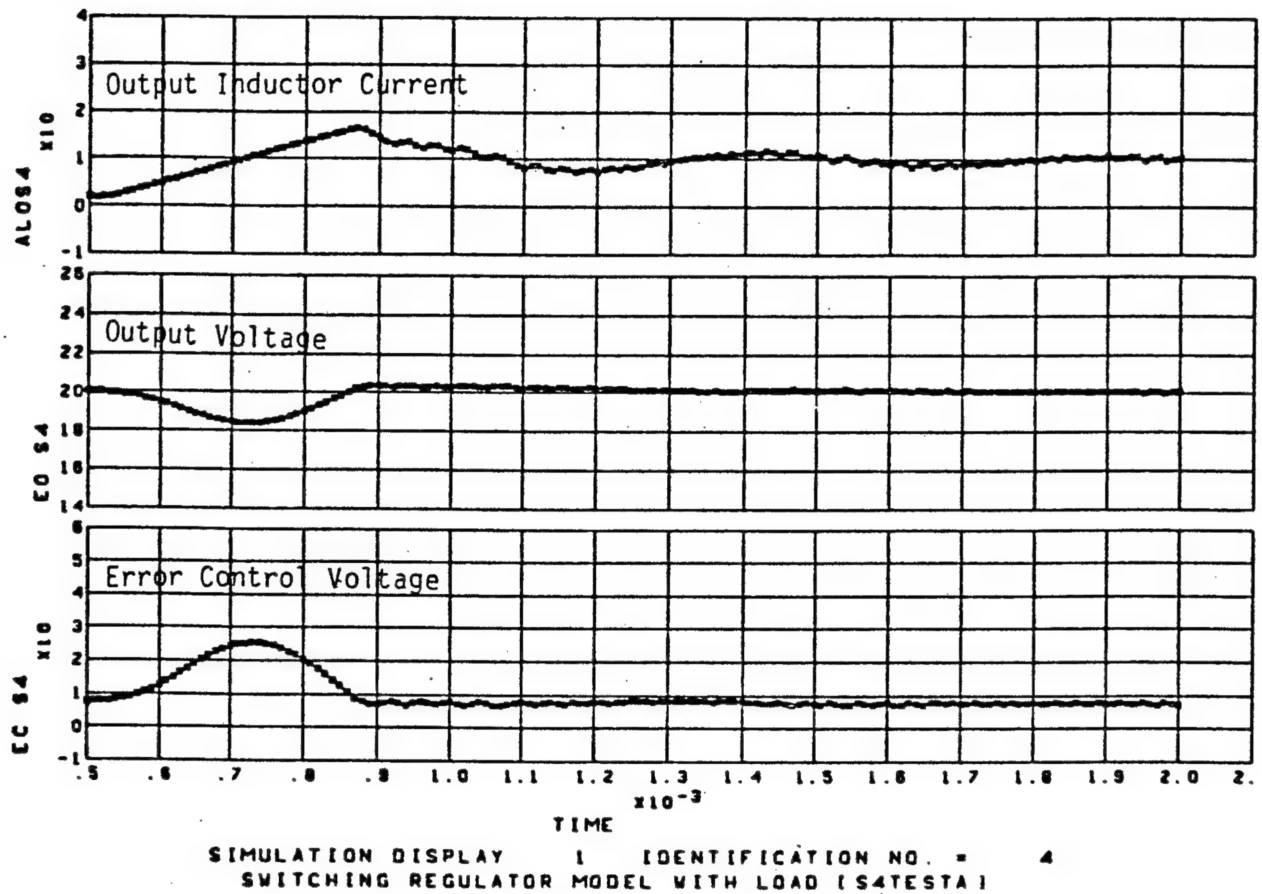


Figure 30 Transient Response (2a) of Switching Regulator with RLC Load

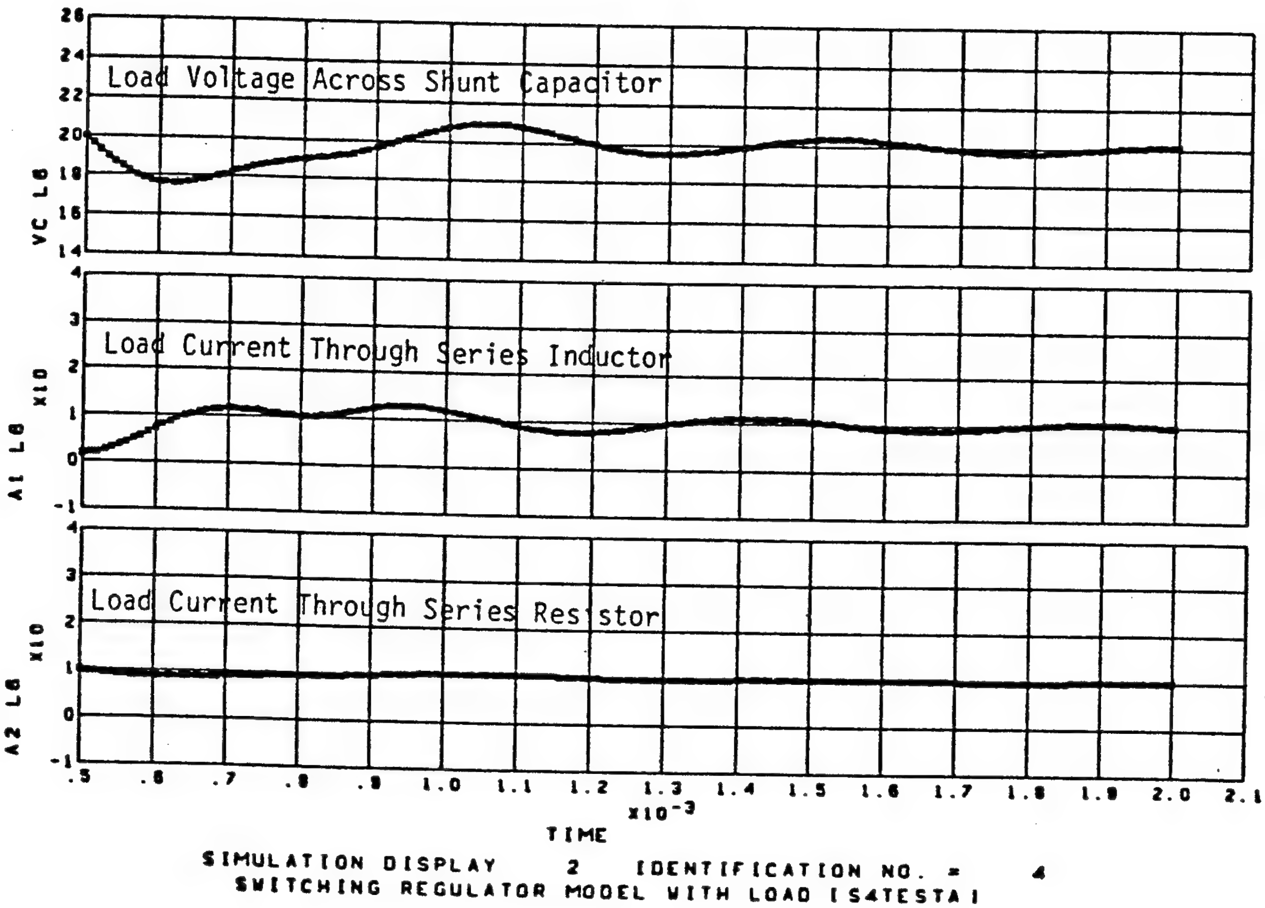


Figure 31 Transient Response (2b) of Switching Regulator with RLC Load

//*/ LINEAR ANALYSIS */*/*/

SWITCHING REGULATOR MODEL WITH LOAD (SATESTA)

80/09/03. 14.42.17.

CASE NO. 1

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 ALOS4	2.0000	.100E-03	1
2 XO S4	20.000	.100E-03	1
3 X1 S4	200.00	.100E-03	1
4 A1 L6	2.0000	.100E-03	1
5 VC L6	20.000	.100E-03	1

RATES AT OP. POINT

1 ALOS4 = -79504. 2 XO S4 = -6121.8 3 X1 S4 = 8111.8

4 A1 L6 = -8363.6 5 VC L6 = 0.

STABILITY MATRIX

	ALOS4	XO S4	X1 S4	A1 L6	VC L6
ALOS4	-60.00	-4000.	0.	308.0	0.
XO S4	3329.	-308.0	0.	-3310.	0.
X1 S4	4.432	-.1425E+05	0.	1097.	0.
A1 L6	0.	.4545E+05	0.	-4182.	-.4545E+05
VC L6	0.	0.	0.	4167.	-416.7

5 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-177.113	+- 2693.24	2699.06	.656204E-01
3	-2306.13	+- 18503.0	18646.2	.123678

CASE NO. 5

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 ALOS4	10.452	.100E-03	1
2 XO S4	20.887	.100E-03	1
3 X1 S4	200.59	.100E-03	1
4 A1 L6	10.346	.100E-03	1
5 VC L6	20.109	.100E-03	1

RATES AT OP. POINT

1 ALOS4 = 38921. 2 XO S4 = 4548.1 3 X1 S4 = -4517.2

4 A1 L6 = -6651.8 5 VC L6 = -33.810

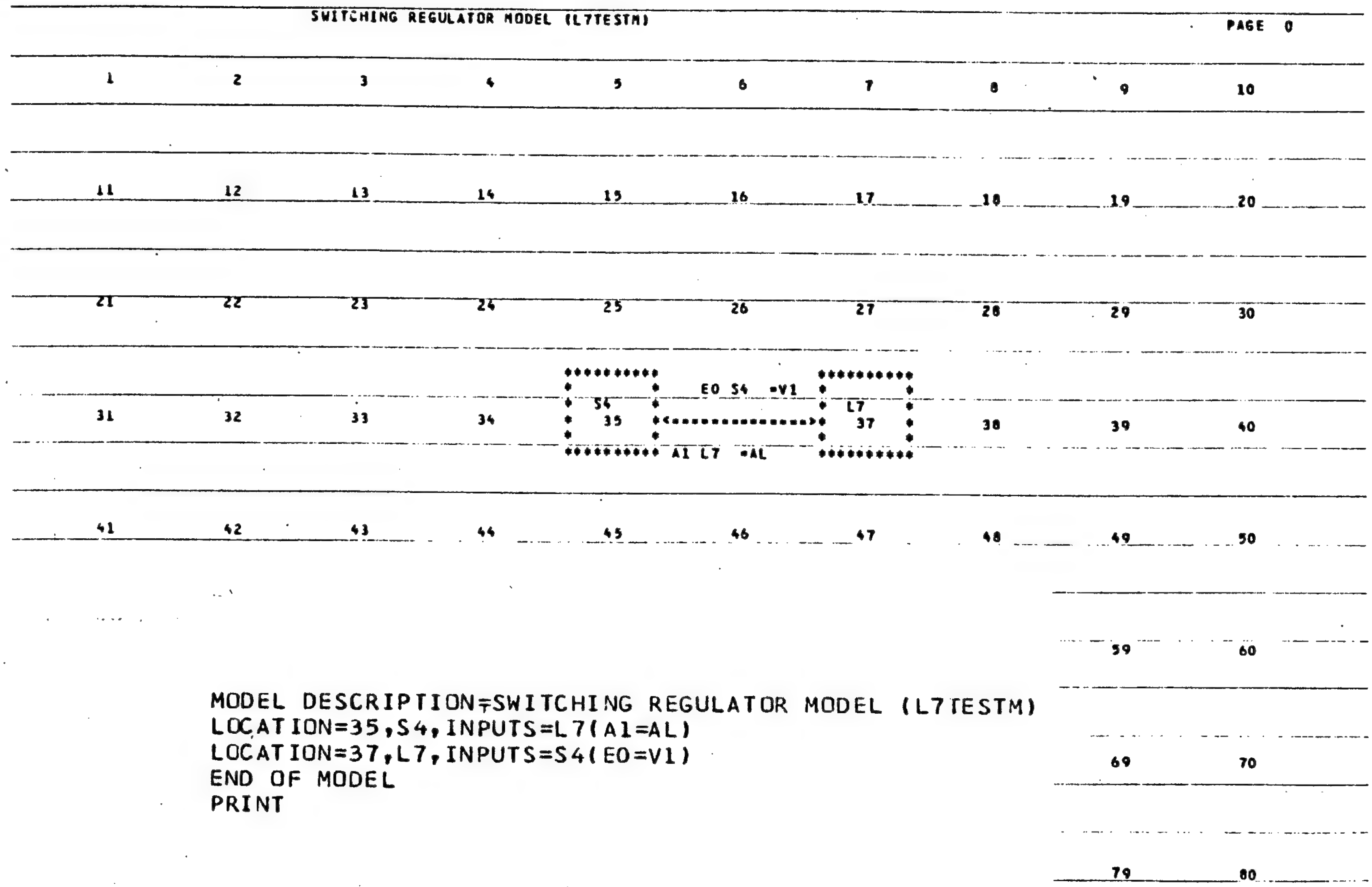
STABILITY MATRIX

	ALOS4	XO S4	X1 S4	A1 L6	VC L6
ALOS4	-60.00	-4000.	0.	308.0	0.
XO S4	3329.	-308.0	0.	-3310.	0.
X1 S4	4.432	-.1425E+05	0.	1097.	0.
A1 L6	0.	.4545E+05	0.	-4182.	-.4545E+05
VC L6	0.	0.	0.	4167.	-2083.

5 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-557.815	+- 2645.07	2703.41	.206708
3	-2757.76	+- 18523.1	18727.2	.147259

Figure 32 Linear Analysis of Switching Regulator with RLC Load




```
MODEL DESCRIPTION=SWITCHING REGULATOR MODEL (L7TESTM)
LOCATION=35,S4,INPUTS=L7(A1=AL)
LOCATION=37,L7,INPUTS=S4(EO=V1)
END OF MODEL
PRINT
```

Figure 33 EASY Model Generation File and Model Schematic for Switching Regulator with Lighting Load

```
TITLE=SWITCHING REGULATOR MODEL WITH LOAD (L7TESTA)
TABLE    AVTL7,8
0.0,.007,.025,.05,.10,.25,.50,1.0
1.31,0.12,0.30,0.43,0.58,0.82,1.30,1.31
PARAMETER VALUES
EI S4=30.0,ER S4=20.0,ET S4=8.0
R2 S4=13500,RO S4=.0015,R1 S4=28700
R3 S4=10000,R4 S4=100000,R5 S4=.077
CO S4=.0003,C1 S4=.0022E-06,C2 S4=.022E-06
LO S4=.00025,N  S4=.065
TS S4=20E-06,TR S4=5E-06
LO L7=22E-06
AM L7=1.0
INITIAL CONDITIONS
XO S4=20.0
X1 S4=208,ALOS4=20.0
A1 L7=20.0
ERROR CONTROLS
XO S4=.0001,X1 S4=.0001,ALOS4=.0001
A1 L7=.0001
PRINT CONTROL=3
PRATE=1
OUTRATE=500
INT MODE=2
TMAX=.1
TINC=1E-06
LINEAR ANALYSIS
PRINTER PLOTS
PLOT ON
SC4020
DISPLAY1
ALOS4,VS,TIME
EO S4,VS,TIME
EC S4,VS,TIME
DISPLAY2
RO L7,VS,TIME
A1 L7,VS,TIME
SIMULATE
XIC-X
LINEAR ANALYSIS
```

Figure 34 EASY Analysis File for Switching Regulator with Lighting Load

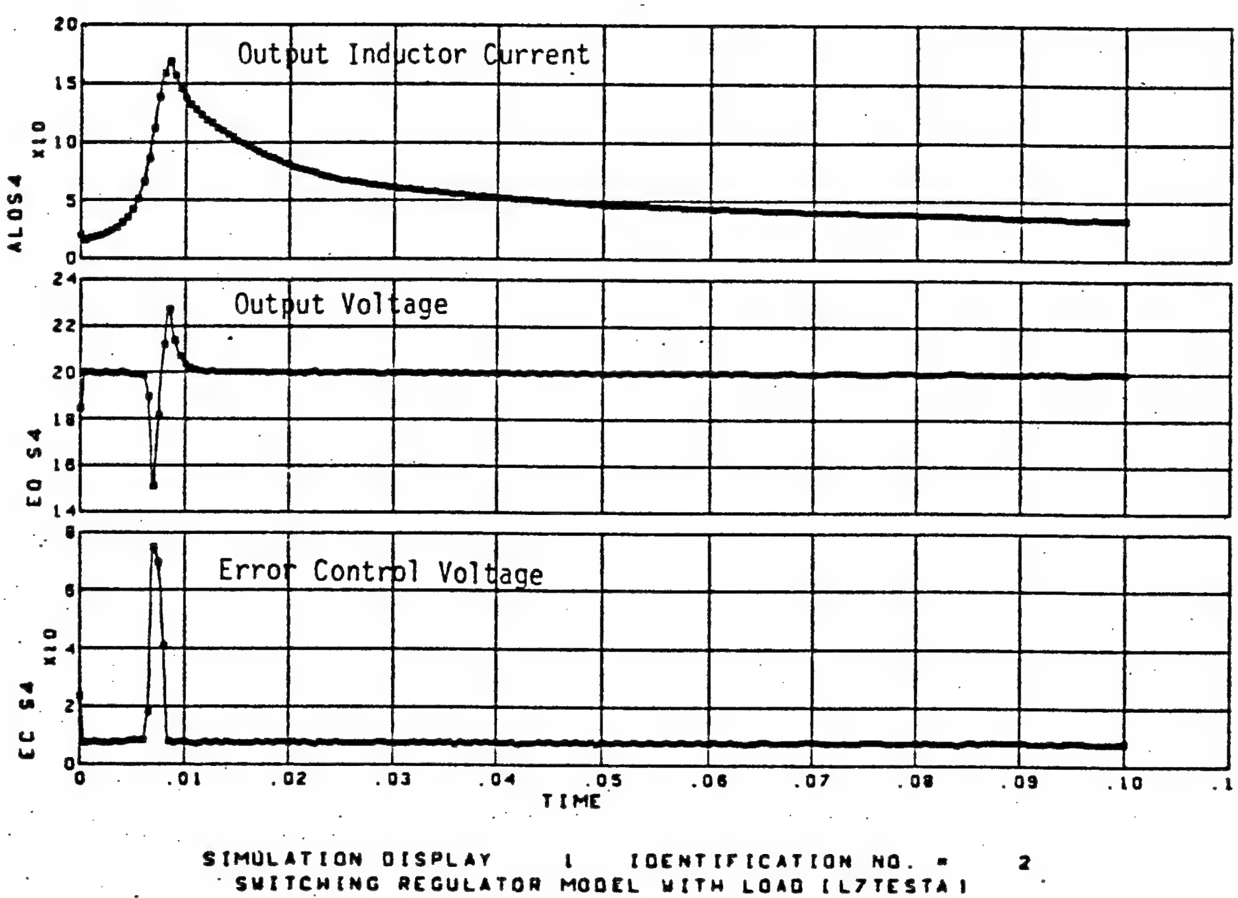


Figure 35 Transient Response (1a) of Switching Regulator with Lighting Load

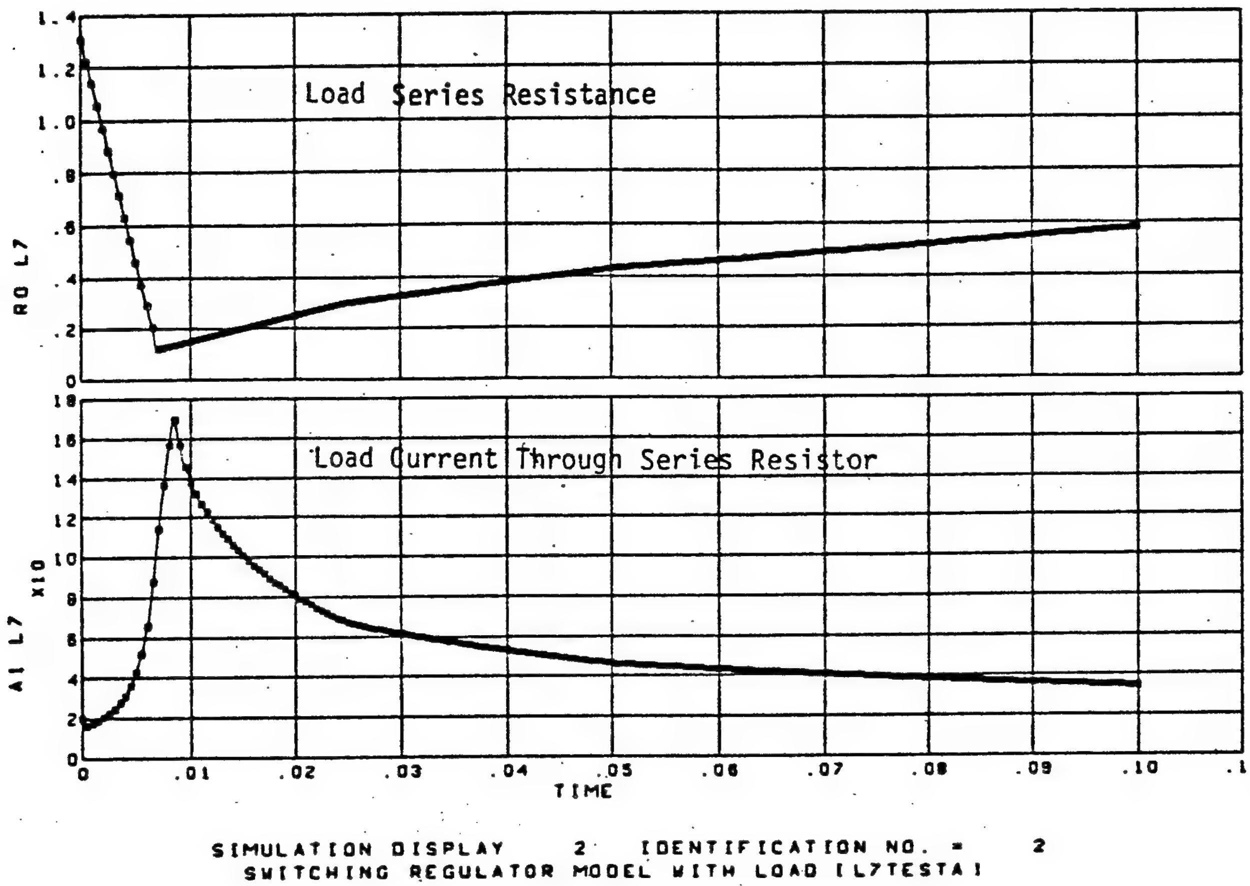


Figure 36 Transient Response (1b) of Switching Regulator with Lighting Load

/*/*/*/ LINEAR ANALYSIS /*/*/*/

SWITCHING REGULATOR MODEL WITH LOAD (L7TESTA)

CASE NO. 1 80/08/21. 20.53.11.

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 ALOS4	20.000	.100E-03	1
2 XO S4	20.000	.100E-03	1
3 X1 S4	208.00	.100E-03	1
4 A1 L7	20.000	.100E-03	1

RATES AT OP. POINT

1 ALOS4 = -73960. 2 XO S4 = -5805.7 3 X1 S4 = 27856.

4 A1 L7 = -.39182E+06

STABILITY MATRIX

	ALOS4	XO S4	X1 S4	A1 L7
ALOS4	-6.000	-4000.	0.	308.0
XO S4	3327.	-308.0	0.	-3310.
X1 S4	.4432	-.1425E+05	0.	1097.
A1 L7	0.	.4545E+05	0.	-.6305E+05

4 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-1407.55	+- 3335.47	3620.30	.388793
3	-60544.4	0.	60544.4	1.00000

CASE NO. 3

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 ALOS4	34.282	.100E-03	1
2 XO S4	22.638	.100E-03	1
3 X1 S4	207.68	.100E-03	1
4 A1 L7	34.492	.100E-03	1

RATES AT OP. POINT

1 ALOS4 = -80133. 2 XO S4 = -7660.2 3 X1 S4 = 6183.9

4 A1 L7 = -.11456E+07

STABILITY MATRIX

	ALOS4	XO S4	X1 S4	A1 L7
ALOS4	-6.000	-4000.	0.	308.0
XO S4	3327.	-308.0	0.	-3310.
X1 S4	.4432	-.1425E+05	0.	1097.
A1 L7	0.	.4545E+05	0.	-.6305E+05

4 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-1407.55	+- 3335.47	3620.30	.388793
3	-60544.4	0.	60544.4	1.00000

Figure 37 Linear Analysis of Switching Regulator with Lighting Load

3.2 FULL HVDC SYSTEM MODEL

The complete HVDC system model simulations conducted show the versatility of the components and the wide range of operating conditions they can simulate. Two system models are developed and dynamically simulated on the EASY program. A block diagram of the HVDC system with its individual components is shown in figure 38. The first system model will have a wound rotor DC generator power source, a flat conductor two-wire distribution system, a buck-type switching regulator with an input EMI filter, and an RLC switched load. The second system will have a solid rotor generator power source, a flat conductor two-wire distribution system, a buck type switching regulator with an input EMI filter, and an RLC switched load.

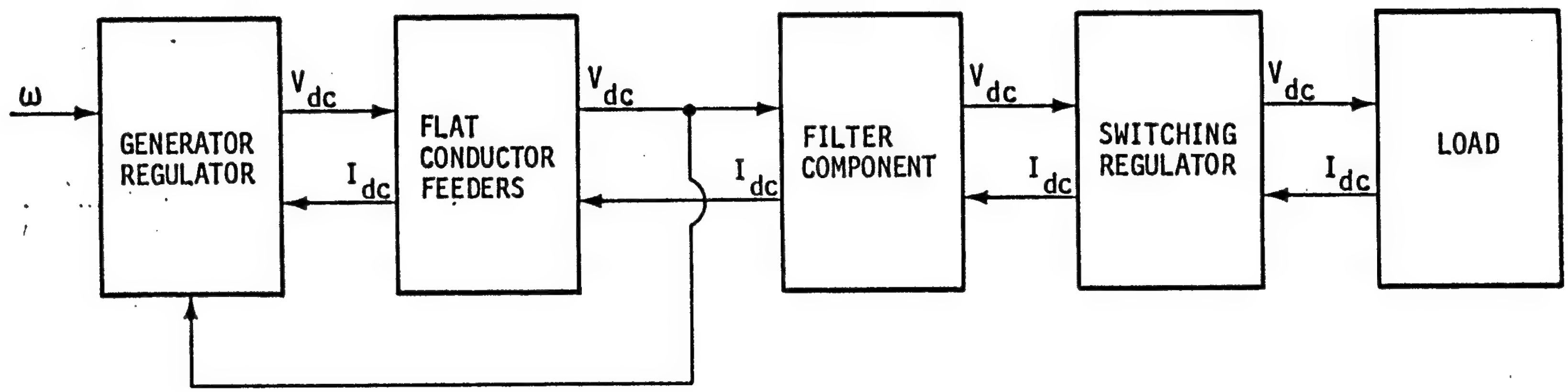
3.2.1 HVDC System with Wound Rotor Generator

The procedures for dynamically simulating the system model are the same as for the two-component model described in Section 3.1. The model must be defined, the required components must be determined, and the system operating point must be specified. The EASY model generation and analysis files for the system model are shown in figures 39 and 40. The model generation file which describes all the interconnections between the model components is submitted to the EASY program which generates the computer printout also included in figure 39.

The analysis file specifies the parameter values that are required by each component, the initial conditions and error controls required by all system state variables, and the types of analyses to be performed. The system model defined in the analysis file has the following electrical requirement characteristics:

1. The wound rotor generator/regulator component is initially operating with a 30VDC output at 85 amps.

2. The flat conductor feeder bus is distributing to parallel buses requiring 30 VDC and 65 amps at bus 1, and requiring 30 VDC and 20 amps at bus 2.



GEN/REG:

3 2 VDC   WOUND ROTOR GENERATOR/REGULATION LOOP

270 VDC   SOLID ROTOR GENERATOR/REGULATOR LOOP

FEEDER:

TWO CONDUCTOR FLAT POWER

DISTRIBUTION BUS

FILTER:

TWO STAGE INPUT EMI

FILTER FOR SWITCHING REG.

SWITCHING REG:

MULTIPLE CONTROL LOOP

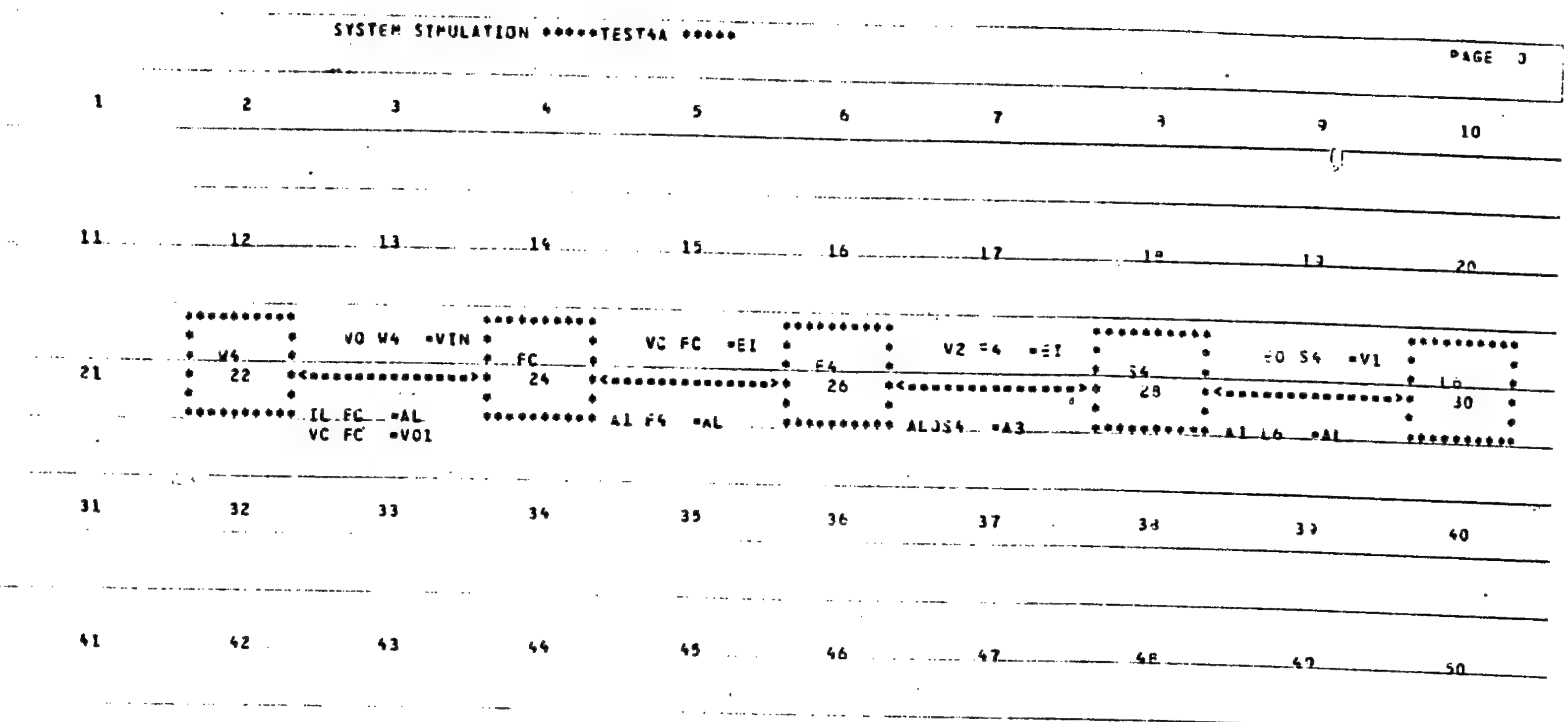
BUCK SWITCHING REGULATOR

LOAD:

ELECTRICAL RLC NETWORK

LIGHTING CIRCUIT

Figure 38 HVDC System Model Block Diagram



```
MODEL DESCRIPTION=SYSTEM SIMULATION *****TEST4A *****
LOCATION=22,W4,INPUTS=FC(IL=AL,VC=VO1)
LOCATION=24,FC,INPUTS=W4(VO=VIN),F4(A1=AL)
LOCATION=26,F4,INPUTS=FC(VC=EI),S4(ALO,A3)
LOCATION=28,S4,INPUTS=F4(V2=EI),L6(A1=AL)
LOCATION=30,Lo,INPUTS=S4(EO=V1)
END OF MODEL
PRINT
```

Figure 39 EASY Model Generation File and Model Schematic for HVDC System with Wound Rotor Generator

```
TITLE=SYSTEM SIMULATION ***** TEST4A *****
PARAMETER VALUES
ER S4=20.0,ET S4=8.0
R2 S4=13500,RO S4=.015,R1 S4=28700
R3 S4=10000,R4 S4=100000,R5 S4=.077
CO S4=.0003,C1 S4=.0022E-06,C2 S4=.022E-06
LO S4=.00025,N  S4=.065
TS S4=20E-06,TR S4=5E-06
RO L6=.015,LO L6=22E-06,CO L6=240E-06
RL L6=1.0
RO W4=0.054,CO W4=880E-06
W  W4=1592,VI W4=30.0
G1 W4=320.0,G2 W4=.025,G3 W4=.0053
K1 W4=0.27,K2 W4=0.732,K3 W4=0.0581
T3 W4=0.12,T2 W4=0.0081
T1 W4=0.0014,T4 W4=0.052
T5 W4=0.13,T6 W4=0.000254
T7 W4=0.151
R1 W4=0.511,K4 W4=0.6494
AL1W4=0.0
PD FC=2.1,EO FC=8.85E-12
WW FC=3.8,WT FC=0.025
PDTFC=.006,SD FC=3.5,SDTFC=.004
RO FC=5.6E-8,WL FC=100.0,MF FC=.3048
SF FC=144.0,L1 FC=6.85E-08,L2 FC=6.85E-08
AL1FC=65.0
L1 F4=309E-06,L2 F4=103E-06,C1 F4=75E-06,C2 F4=20E-06
R1 F4=.0237,R2 F4=.0159,RA F4=2.12
INITIAL CONDITIONS
XO S4=20.0
X1 S4=208,ALOS4=20.0
VC L6=20.0,A1 L6=20.0
IL FC=85.0,VC FC=30.0
AF W4=3.55,AEXW4=0.2923
VR W4=0.1093,VF W4=0.1093
VO W4=30.0,XR W4=.1093,XF W4=.002296
A1 F4=20.0,A2 F4=20.0,V1 F4=30.0,V2 F4=30.0
ERROR CONTROLS
XO S4=.0001,X1 S4=.0001,ALOS4=.0001
VC L6=.0001,A1 L6=.0001
IL FC=.0001,VC FC=.0001
AF W4=.0001,AEXW4=.0001,VR W4=.0001
VO W4=.0001,VF W4=.0001,XR W4=.0001
XF W4=.0001
A1 F4=.0001,A2 F4=.0001,V1 F4=.0001,V2 F4=.0001
PRINT CONTROL=3
PRATE=4
OUTRATE=50
INT MODE=2
TMAX=.01
TINC=1E-06
LINEAR ANALYSIS
PRINTER PLOTS
PLOT ON
SC4020
SI MANUAL SCALES
```

Figure 40 EASY Analysis File for HVDC System with Wound Rotor Generator

```
DISPLAY1
VO W4,VS,TIME,YRANGE=0,100
AF W4,VS,TIME,YRANGE=3,4
AEXW4,VS,TIME,YRANGE=0,5
DISPLAY2
IL FC,VS,TIME,YRANGE=0,100
VC FC,VS,TIME,YRANGE=25,35
DISPLAY3
A1 F4,VS,TIME,YRANGE=-10,40
V1 F4,VS,TIME,YRANGE=0,100
A2 F4,VS,TIME,YRANGE=-10,40
V2 F4,VS,TIME,YRANGE=0,100
DISPLAY4
ALOS4,VS,TIME,YRANGE=0,30
EO S4,VS,TIME,YRANGE=15,25
EC S4,VS,TIME,YRANGE=0,30
DISPLAY5
VC L6,VS,TIME,YRANGE=15,40
A1 L6,VS,TIME,YRANGE=0,40
A2 L6,VS,TIME,YRANGE=0,40
SIMULATE
XIC-X
INITIAL TIME=.01
LINEAR ANALYSIS
PARAMETER VALUES
RL L6=0.5
AL1FC=85.0
TMAX=.02
SIMULATE
XIC-X
LINEAR ANALYSIS
```

Figure 40 EASY Analysis File For HVDC System With Wound Rotor Generator

(Continued)

3. The switching regulator with EMI filter is operating with a 30 volt input and a 20 volt output at an average of 20 amps.

4. The load bus resistive, capacitive and inductive elements initially require 20 volts at 20 amps.

The analyses requested by the analysis file include linear analysis and dynamic simulations. The system model first has a linear analysis performed on it to determine stability about the initial operating point. The linear analysis of the HVDC system model (shown in figure 41) shows the system is at a stable point. With the intial conditions described, the system is dynamically simulated for 10 milliseconds. This allows for the turn-on transients to sufficiently die out and for the system to operate in a steady state mode. A linear analysis is requested at the end of this simulation with the new operating point variables. Again the system is shown to be stable (figure 42).

The transient responses of selected variables in the system are shown in figures 43 through 47. The system remains stable throughout this simulation with the generator/regulator output voltage holding constant (figure 43), the EMI filter isolating the switching regulator operating frequency from the distribution bus, (figure 44 and 45), and the switching regulator maintaining the load voltage within the desirable tolerance (figure 46 and 47).

Before a second simulation is performed some system loading parameters are changed. The total current through the feeder component is increased to 125 amps with the switching regulator load (bus 2) increasing from 20 amps to 40 amps and the bus 1 load increasing from 65 amps to 85 amps. An additional 10 milliseconds of time is requested to be simulated with a linear analysis requested at the completion of this simulation. The results of the linear analysis shown in figure 48 shows that the system is stable at this operating point.

The transient response characteristics of the selected variables to the load application are shown in figures 49 through 53. The results are well within the predictable ranges for this type of load change on this predefined stable

/*/*/*/ LINEAR ANALYSIS /*/*/*/

SYSTEM SIMULATION ***** TEST4A *****

CASE NO. 1 80/09/23. 19.47.21.

	STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1	AF W4	3.5500	.100E-03	1
2	AEXW4	.29230	.100E-03	1
3	VR W4	.10930	.100E-03	1
4	XR W4	.10930	.100E-03	1
5	VF W4	.10930	.100E-03	1
6	XF W4	.22960E-02	.100E-03	1
7	VO W4	30.000	.100E-03	1
8	IL FC	85.000	.100E-03	1
9	VC FC	30.000	.100E-03	1
10	A1 F4	20.000	.100E-03	1
11	V1 F4	30.000	.100E-03	1
12	V2 F4	30.000	.100E-03	1
13	A2 F4	20.000	.100E-03	1
14	ALOS4	20.000	.100E-03	1
15	XO S4	20.000	.100E-03	1
16	X1 S4	205.00	.100E-03	1
17	A1 L6	20.000	.100E-03	1
18	VC L6	20.000	.100E-03	1

RATES AT OP. POINT

1 AF W4	= -4.6841	2 AEXW4	= -36.386	3 VR W4	= 0.	4 XR W4	= 0.
6 XF W4	= .35400E-04	7 VO W4	= -479.96	8 IL FC	= -.10533E+08	9 VC FC	= 0.
11 V1 F4	= 0.	12 V2 F4	= 0.	13 A2 F4	= -3037.4	14 ALOS4	= -75040.
16 X1 S4	= 27936.	17 A1 L6	= -93636.	18 VC L6	= 0.		

5 VF W4 = .20874E-01
10 A1 F4 = -1334.0
15 XO S4 = -5778.1

STABILITY MATRIX NOT SHOWN

18 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-6.57095	0.	6.51095	1.00000
3	-6.25473	0.	6.21473	1.00000
4	-256.002	+- 26322.5	26313.7	.972515E-02
5	-349.054	0.	349.054	1.00000
6	-900.920	0.	900.920	1.00000
7	-1031.86	+- 2512.54	2711.16	.379902
8	-2430.35	+- 5930.97	6401.60	.379174
9	-3326.36	+- 18479.4	18716.4	.177156
10	-11432.5	+- 19464.5	22513.6	.506451
11	-20719.1	0.	20719.1	1.00000
12	-61933.3	+- .533784E+07	.531820E+07	.116019E-01

Figure 41 Linear Analysis (1) of HVDC System with Wound Rotor Generator

/*/*/*/ LINEAR ANALYSIS /*/*/*/

SYSTEM SIMULATION ***** TEST42 *****

CASE NO. 3 80/09/23. 19.51.33.

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 AF W4	3.7063	.100E-03	1
2 AEXW4	.29690	.100E-03	1
3 VR W4	.11615	.100E-03	1
4 XR W4	.11047	.100E-03	1
5 VF W4	.11620	.100E-03	1
6 XF W4	.232868E-02	.100E-03	1
7 VO W4	31.289	.100E-03	1
8 IL FC	84.711	.100E-03	1
9 VC FC	29.648	.100E-03	1
10 A1 F4	19.703	.100E-03	1
11 V1 F4	29.376	.100E-03	1
12 V2 F4	29.140	.100E-03	1
13 A2 F4	19.710	.100E-03	1
14 ALOS4	19.710	.100E-03	1
15 XO S4	21.514	.100E-03	1
16 X1 S4	207.69	.100E-03	1
17 A1 L6	19.707	.100E-03	1
18 VC L6	19.706	.100E-03	1

RATES AT OP. POINT

1 AF W4	= -4.1709	2 AEXW4	= -215.69	3 VR W4	= -.54936	4 XR W4	= .409665E-01
6 XF W4	= -.43955E-02	7 VO W4	= 9.8631	8 IL FC	= 18715.	9 VC FC	= 11227.
11 V1 F4	= -22.712	12 V2 F4	= -3.2765	13 A2 F4	= -763.24	14 ALOS4	= 35366.
16 X1 S4	= -2563.4	17 A1 L6	= -220.36	18 VC L6	= 4.7521		

5 VF W4	= -2.6892
10 A1 F4	= 22.105
15 XO S4	= 2734.7

STABILITY MATRIX NOT SHOWN

18 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-6.46930	0.	6.46930	1.00000
3	-8.20699	0.	8.20699	1.00000
4	-255.974	+- 26322.5	26323.7	.972410E-02
5	-350.753	0.	350.753	1.00000
6	-899.438	0.	899.438	1.00000
7	-959.823	+- 1379.92	1680.91	.571015
8	-3479.17	+- 18332.7	18659.9	.186451
9	-8527.11	+- 7560.17	13053.6	.659175
10	-7154.90	+- 22936.8	24026.9	.297788
11	-20719.2	0.	20719.2	1.00000
12	-61933.3	+- .533764E+07	.533820E+07	.116019E-01

Figure 42 Linear Analysis (2) of HVDC System with Wound Rotor Generator

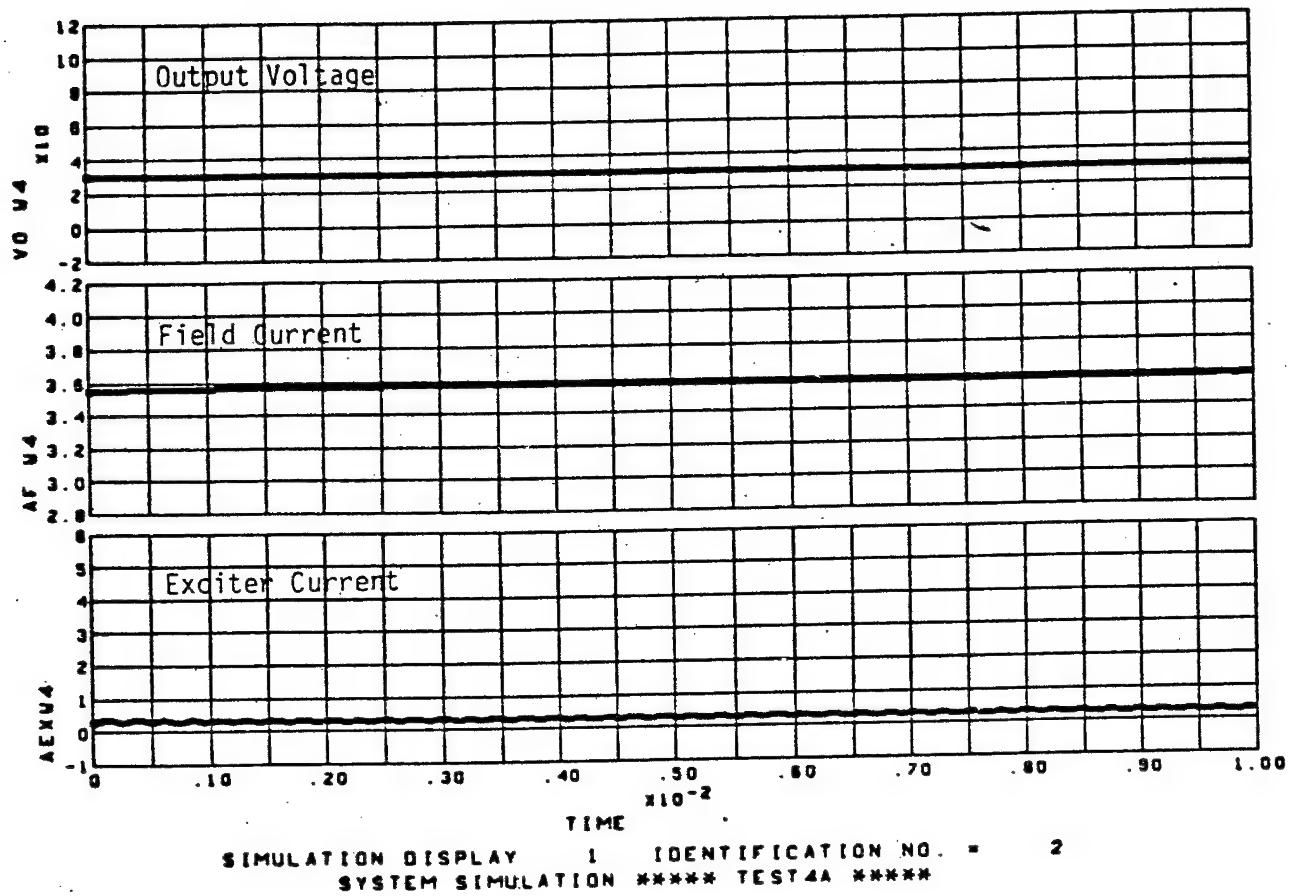


Figure 43 Transient Response (1a) of Wound Rotor Generator

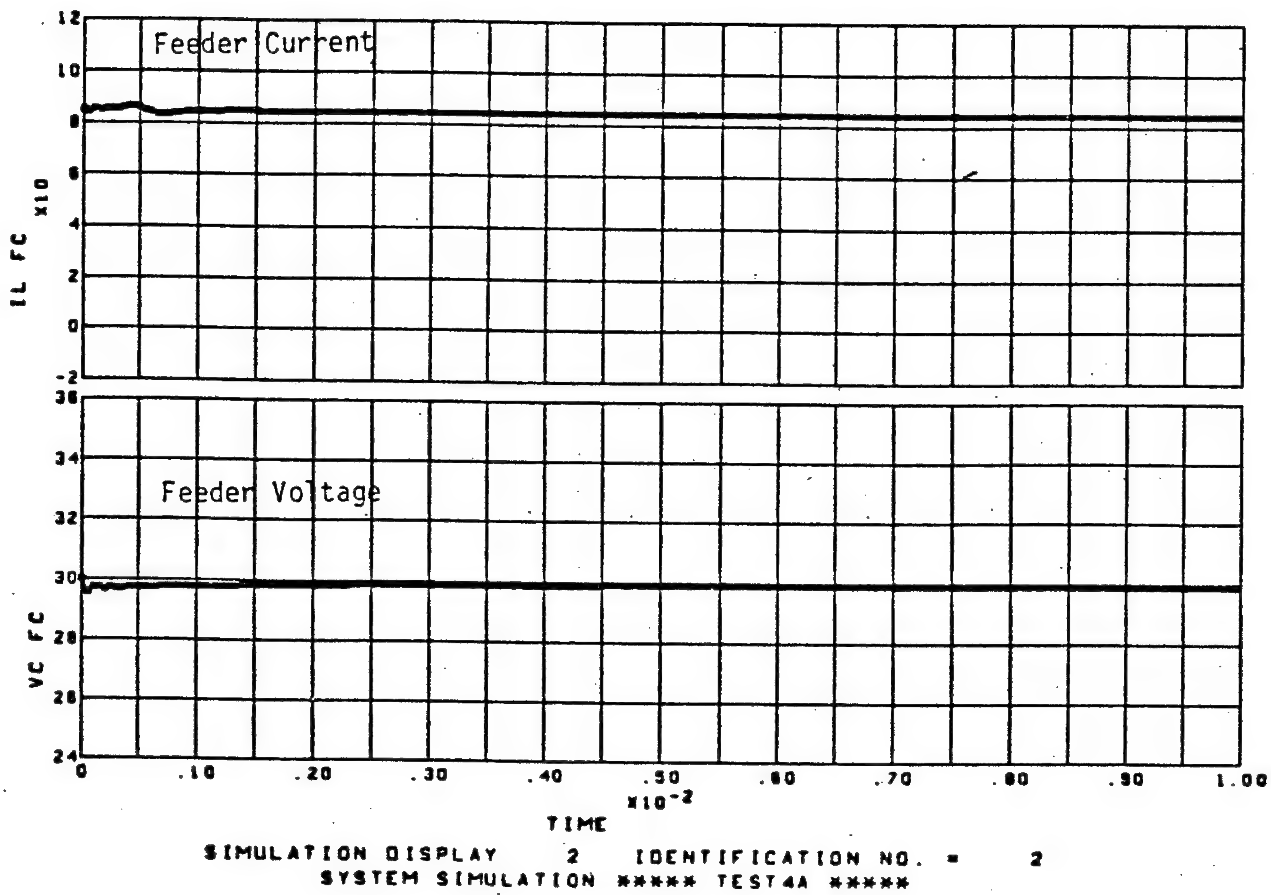


Figure 44 Transient Response (1b) of Flat Conductor Feeder

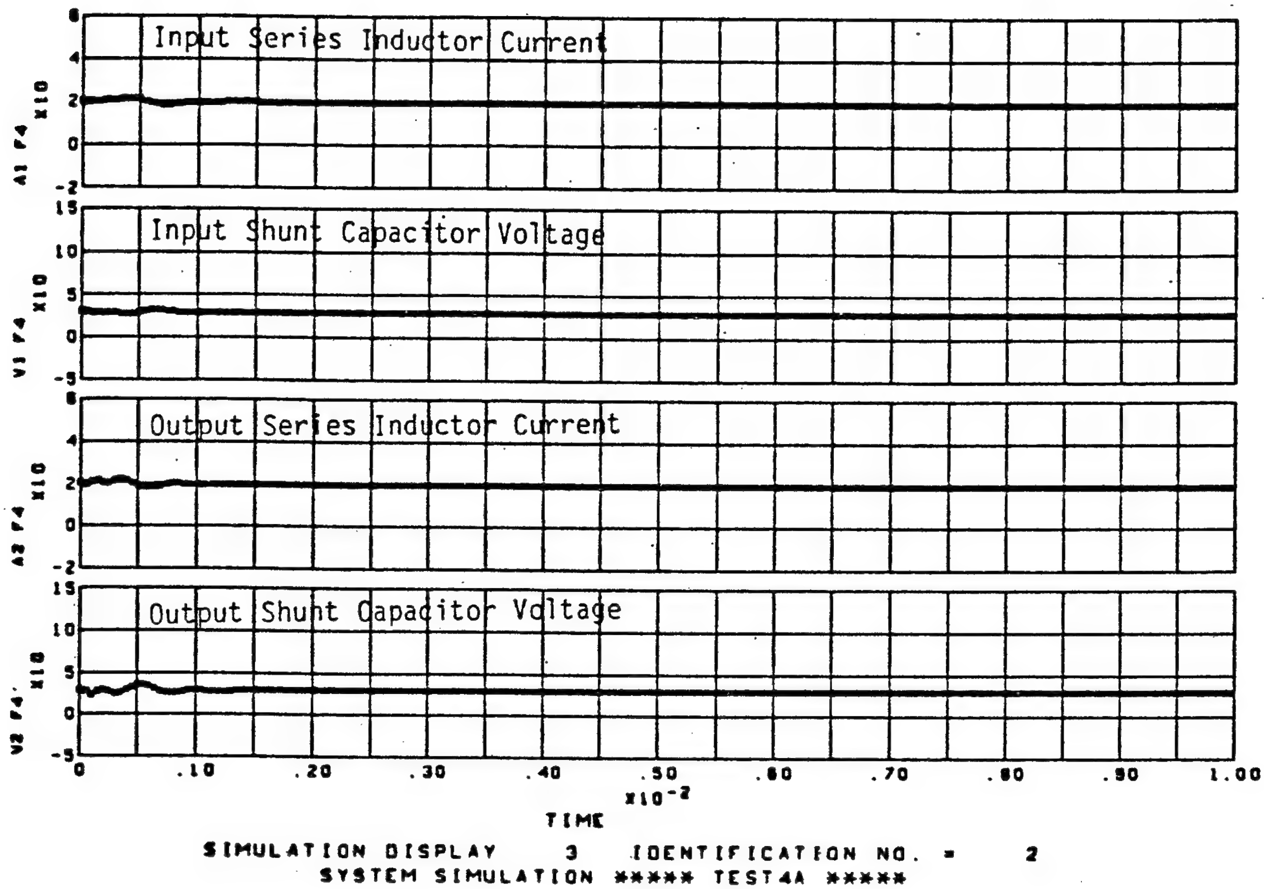


Figure 45 Transient Response (1c) of Switching Regulator EMI Filter

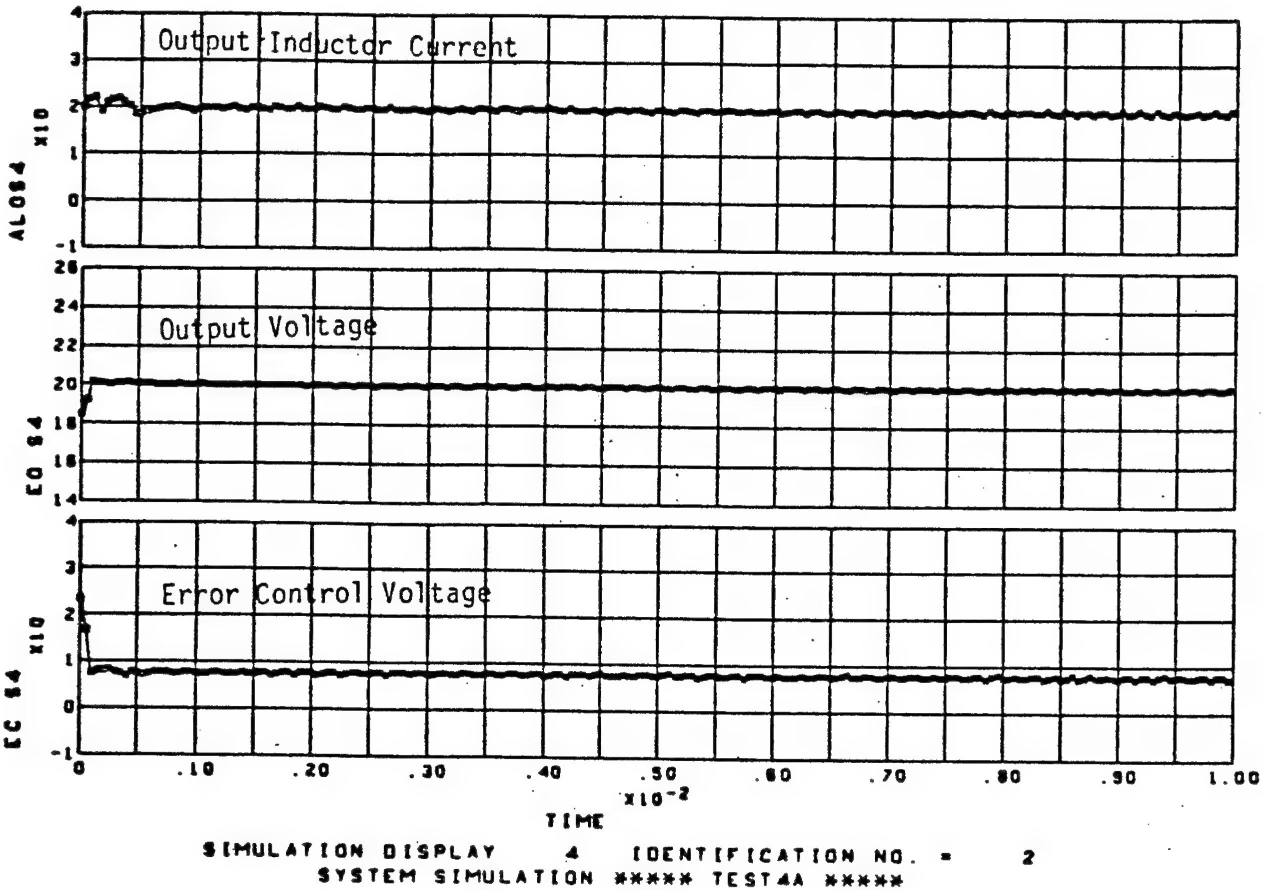


Figure 46 Transient Response (1d) of Switching Regulator

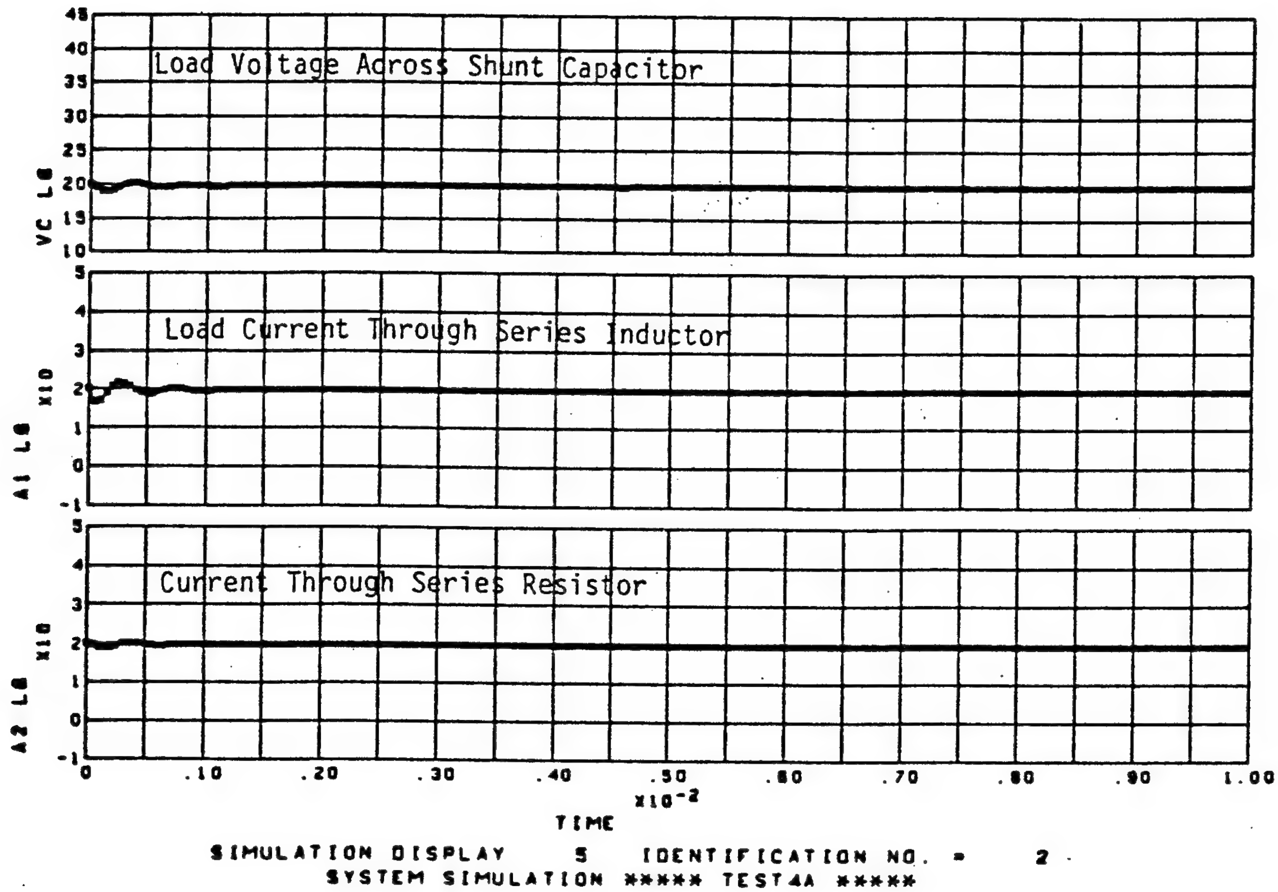


Figure 47 Transient Response (1e) of RLC Load

/*/*/*/ LINEAR ANALYSIS /*/*/*/

SYSTEM SIMULATION ***** TEST4A *****

CASE NO. 5 80/09/23. 19.54.23.

	STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1	AF W4	3.7065	.100E-03	1
2	AEXW4	.38073	.100E-03	1
3	VR W4	.13935	.100E-03	1
4	XR W4	.11269	.100E-03	1
5	VF W4	.13936	.100E-03	1
6	XF W4	.24089E-02	.100E-03	1
7	VO W4	31.274	.100E-03	1
8	TL FC	123.84	.100E-03	1
9	VC FC	29.173	.100E-03	1
10	A1 F4	38.335	.100E-03	1
11	V1 F4	28.245	.100E-03	1
12	V2 F4	27.577	.100E-03	1
13	A2 F4	39.844	.100E-03	1
14	ALOS4	39.111	.100E-03	1
15	XO S4	23.015	.100E-03	1
16	X1 S4	207.73	.100E-03	1
17	A1 L6	38.843	.100E-03	1
18	VC L6	19.419	.100E-03	1

RATES AT OP. POINT

1 AF W4	= -1.0678	2 AEXW4	= -60.677	3 VR W4	= .90420E-01	4 XR W4	= .2232E
6 XF W4	= .30552E-02	7 VO W4	= 3.5927	8 TL FC	= -12673.	9 VC FC	= 1311.[illegible]
11 V1 F4	= -114.54	12 V2 F4	= -13330.	13 A2 F4	= 329.44	14 ALOS4	= 27[illegible]54.
16 X1 S4	= -2406.5	17 A1 L6	= 1033.3	18 VC L6	= 26.041		

5 VF W4	= -.47402
10 A1 F4	= 7[illegible].365
15 XO S4	= 3336.1

STABILITY MAXTIX NOT SHOWN

18 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-6.41572	0.	6.41572	1.00000
3	-8.16947	0.	8.16947	1.00000
4	-255.974	+- 26322.5	26323.7	.972410E-02
5	-353.700	0.	353.700	1.00000
6	-885.812	0.	885.812	1.00000
7	-1268.70	0.	1268.70	1.00000
8	-2437.58	0.	2437.58	1.00000
9	-4623.57	+- 18023.3	18606.9	.248437
10	-6677.13	+- 7518.23	10055.2	.664045
11	-7155.89	+- 22946.6	24038.4	.297686
12	-20719.2	0.	20719.2	1.00000
13	-61933.3	+- .533784E+07	.533820E+07	.116019E-01

Figure 48 Linear Analysis (3) of HVDC System with Wound Rotor Generator

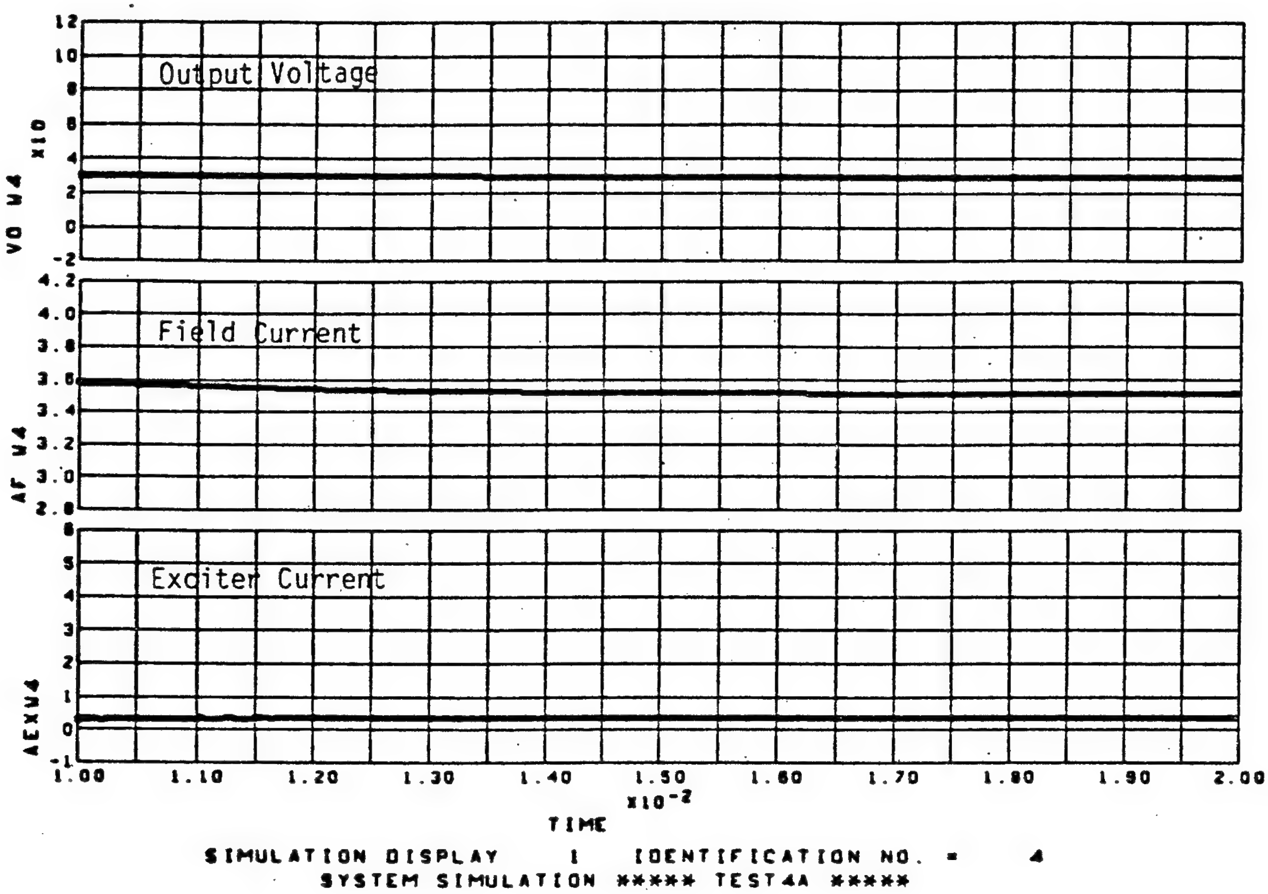


Figure 49 Transient Response (2a) of Wound Rotor Generator

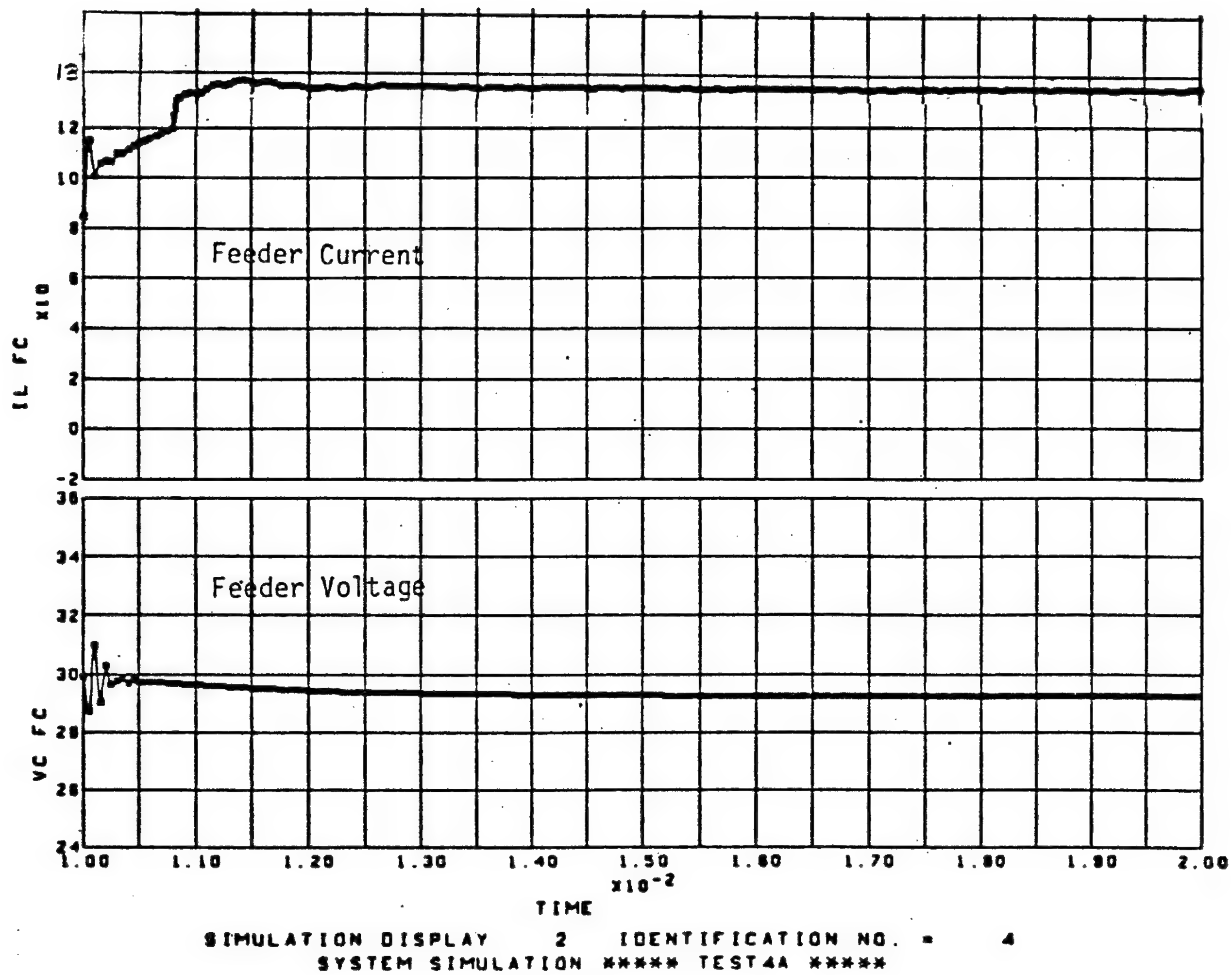


Figure 50 Transient Response (2b) of Flat Conductor Feeder

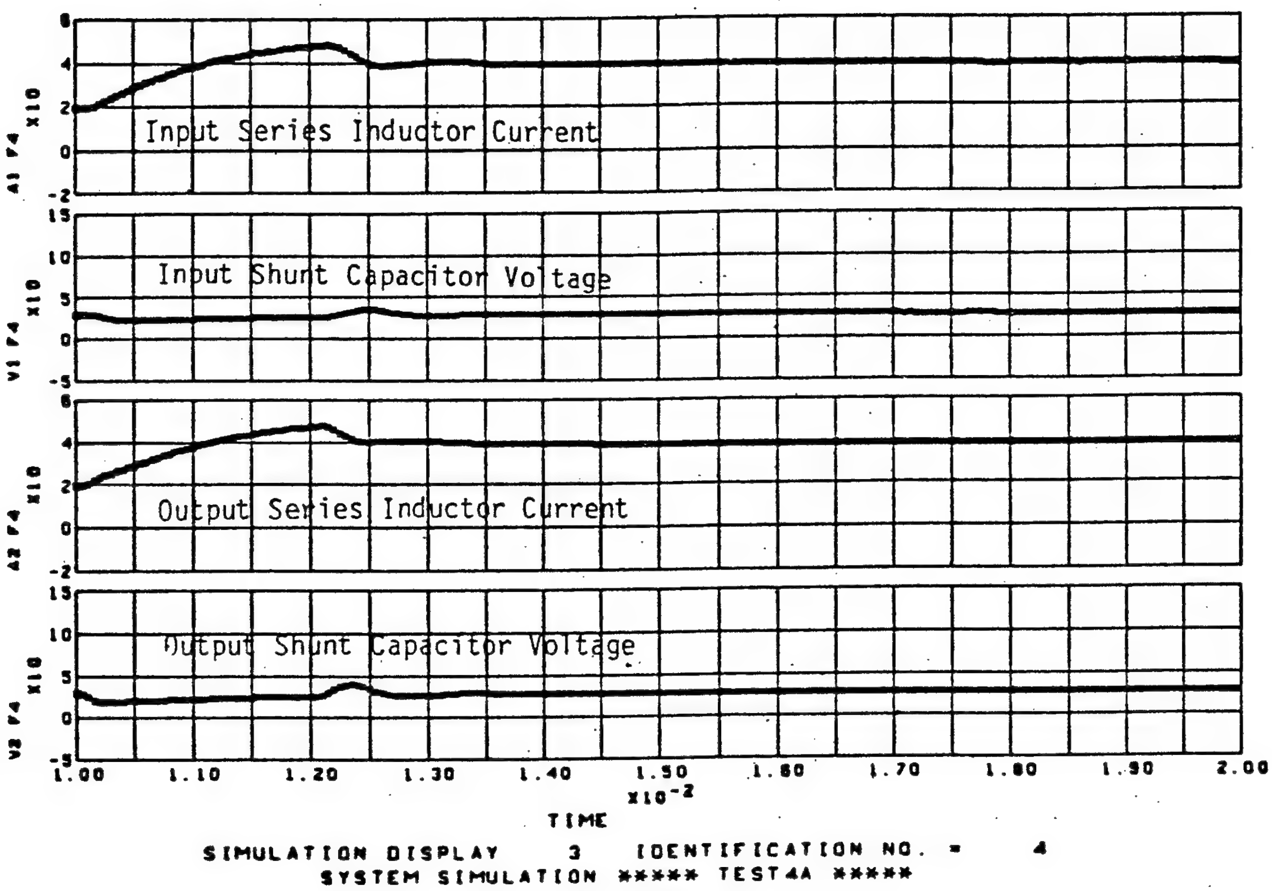


Figure 51 Transient Response (2c) of Switching Regulator EMI Filter

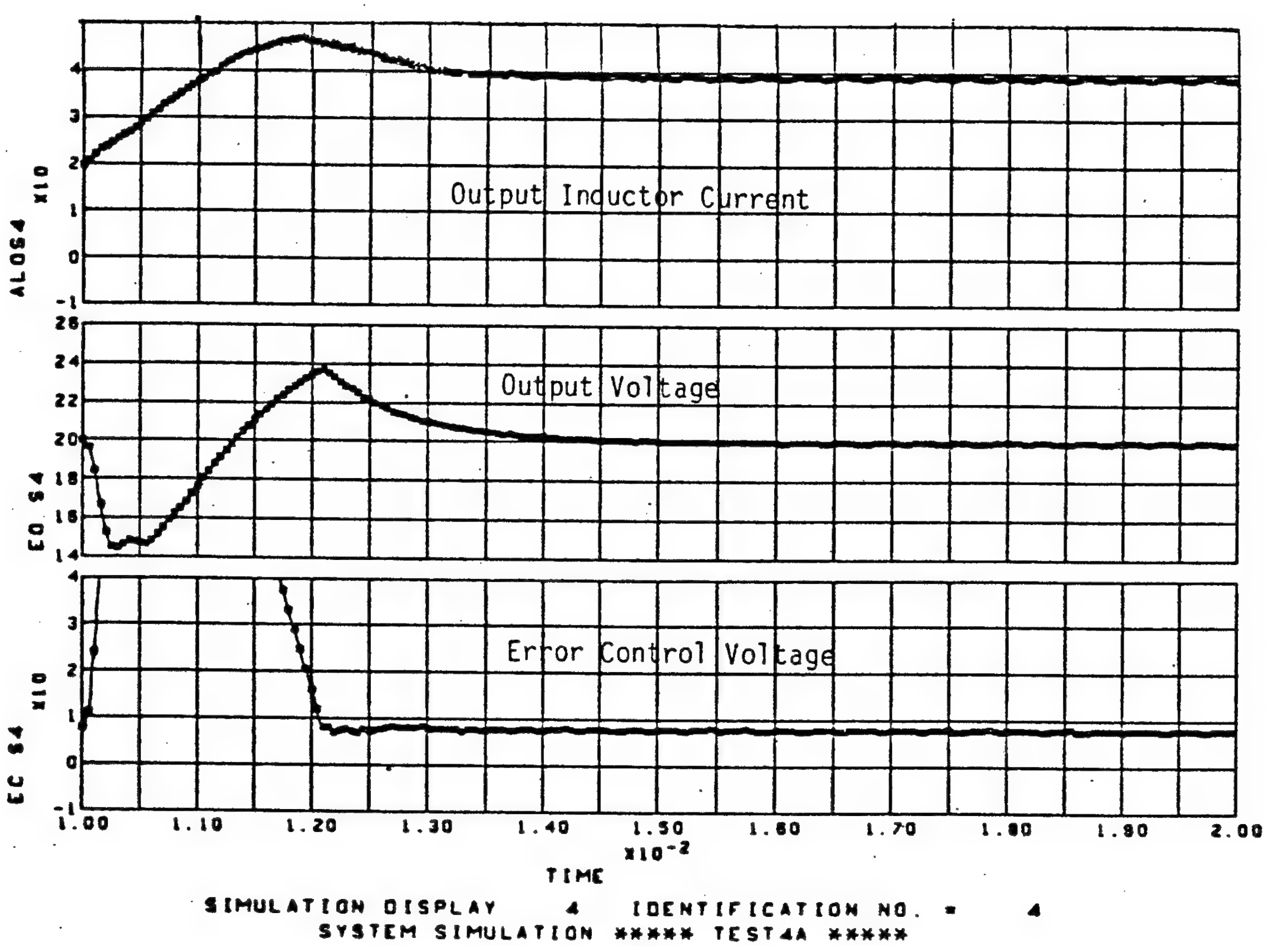


Figure 52 Transient Response (2d) of Switching Regulator

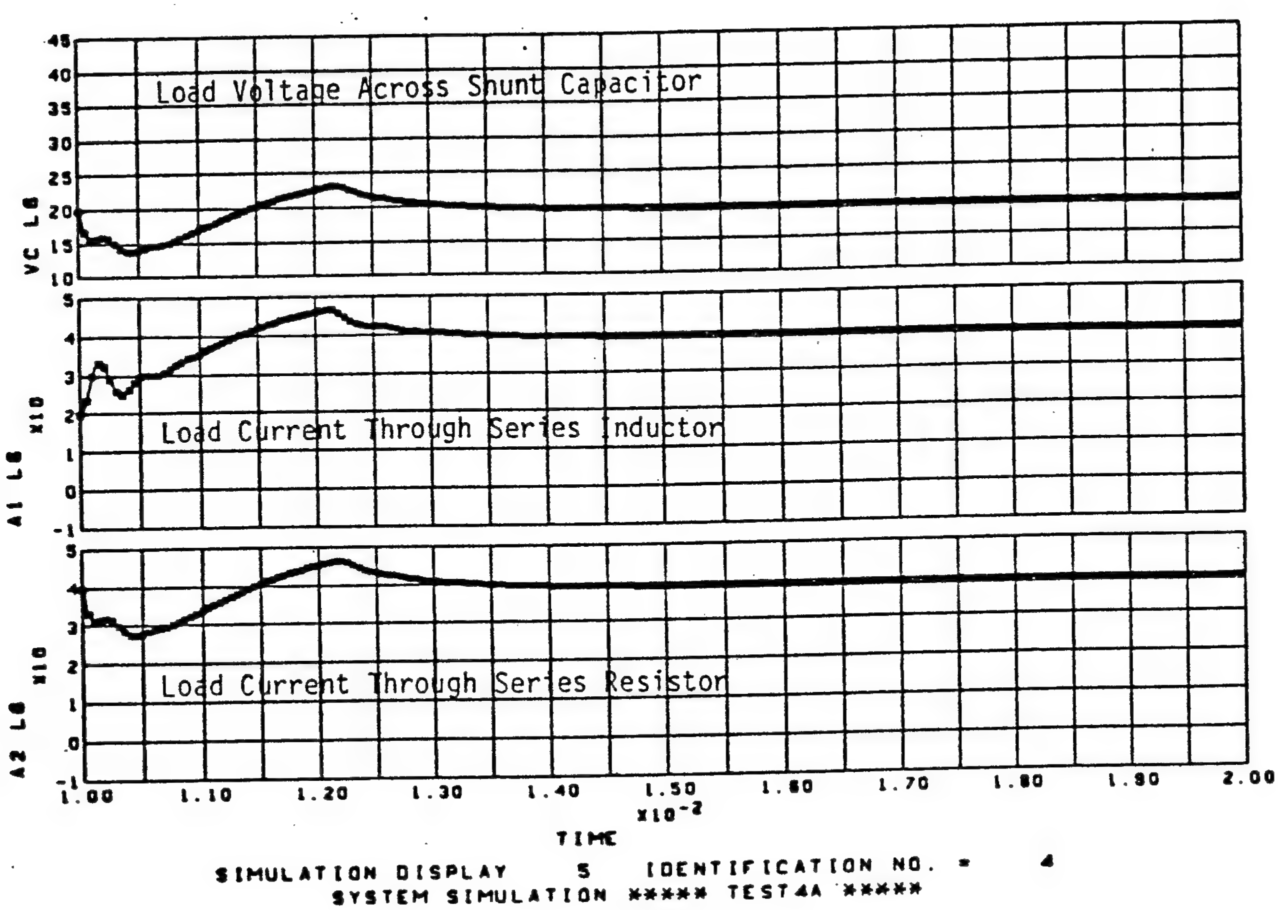


Figure 53 Transient Response (2e) of RLC Load

system and the system remains stable as it should. For future studies, however, the appropriate parameter values may be changed in the components to reflect new system conditions or designs and the stability limits of the system can be evaluated.

3.2.2 HVDC System with Solid Rotor Generator

The solid rotor generator/regulator HVDC system model is defined in the EASY model generation and analysis files shown in figures 54 and 55. The EASY program computer printout of the model is included with the model generation file in figure 54.

The analysis file specifies the system model which has the following electrical requirement characteristics.

1. The solid rotor generator/regulator component is initially operating with a 270 VDC output at 40 amps.

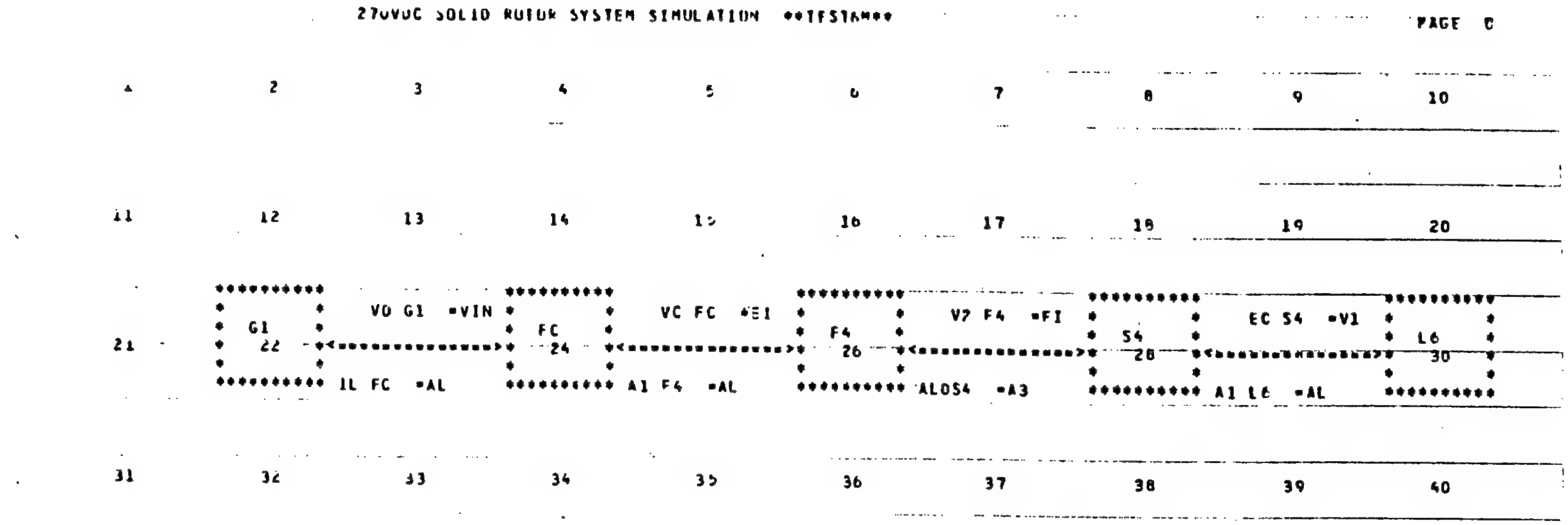
2. The flat conductor feeder bus is distributing to parallel buses requiring 270 VDC and 40 amps at bus 1 and no load at bus 2.

3. The switching regulator with EMI filter is operating with a 270 VDC input and a 28 VDC output at an average of 40 amps.

4. The RLC load component initially demands 28 VDC at 40 amps.

The analyses requested by the analysis file include linear analysis and dynamic simulations. The system model first has a linear analysis perfomed on it (figure 56) which shows the system to be stable at the initial operating point.

With the initial conditions described, the system is dynamically simulated for 10 milliseconds. As in the preceding case, this allows for the turn-on transient to die out and the system to operate in a steady state mode. Most system time constants are short compared to this time interval of simulation, therefore, a good picture of system operation and its relative stability can be obtained. A linear analysis is requested at the end of this simulation




```
MODEL DESCRIPTION=270VDC SOLID ROTOR SYSTEM SIMULATION  **TEST6M**
LOCATION=22,G1,INPUTS=FC(IL=AL)
LOCATION=24,FC,INPUTS=G1(VO=VIN),F4(A1=AL)
LOCATION=26,F4,INPUTS=FC(VC=EI),S4(ALO,A3)
LOCATION=28,S4,INPUTS=F4(V2=EI),L6(A1=AL)
LOCATION=30,L6,INPUTS=S4(EO=V1)
END OF MODEL
PRINT
```

Figure 54 EASY Model Generation File and Model Schematic for HVDC System with Solid Rotor Generator

```
TITLE=270VDC SOLID ROTOR SYSTEM SIMULATION ***** TEST6A *****
PARAMETER VALUES
ER S4=28.0,ET S4=3.0
R2 S4=13500,RO S4=.015,R1 S4=45200
R3 S4=10000,R4 S4=100000,R5 S4=.077
CO S4=.0003,C1 S4=.0022E-06,C2 S4=.022E-06
LO S4=.00025,N  S4=.065
TS S4=10E-06,TR S4=5E-06
RO L6=.015,LO L6=22E-06,CO L6=240E-06
RL L6=0.7
VR G1=270.0
L1 G1=65E-06,L2 G1=85E-06,CO G1=12.5E-06
RO G1=1.0,K1 G1=0.685,K2 G1=10.0
T1 G1=0.0166,T2 G1=.003
PDRG1=135.0
AL1G1=0.0
PD FC=2.1,EO FC=8.85E-12
WW FC=3.8,WT FC=0.025
PDTFC=.006,SD FC=3.5,SDTFC=.004
RO FC=5.6E-8,WL FC=100.0,MF FC=.3048
SF FC=144.0,L1 FC=6.85E-08,L2 FC=6.85E-08
AL1FC=0.0
L1 F4=309E-06,L2 F4=103E-06,C1 F4=75E-06,C2 F4=20E-06
R1 F4=.0237,R2 F4=.0159,RA F4=2.12
INITIAL CONDITIONS
XO S4=28.0
X1 S4=288,ALOS4=40.0
VC L6=28.0,A1 L6=40.0
IL FC=40.0,VC FC=270.0
VO G1=270.0,ALOG1=40.0
V2 G1=.2783,X3 G1=-.0378
A1 F4=40.0,A2 F4=40.0,V1 F4=270.0,V2 F4=270.0
ERROR CONTROLS
XO S4=.0001,X1 S4=.0001,ALOS4=.0001
VC L6=.0001,A1 L6=.0001
IL FC=.0001,VC FC=.0001
VO G1=.0001,ALOG1=.0001
V2 G1=.0001,X3 G1=.0001
A1 F4=.0001,A2 F4=.0001,V1 F4=.0001,V2 F4=.0001
PRINT CONTROL=3
PRATE=4
OUTRATE=50
INT MODE=2
TMAX=.01
TINC=1E-06
LINEAR ANALYSIS
PRINTER PLOTS
PLOT ON
SC4020
SI MANUAL SCALES
DISPLAY1
VO G1,VS,TIME,YRANGE=100,400
ALOG1,VS,TIME,YRANGE=0,100
DISPLAY2
IL FC,VS,TIME,YRANGE=0,200
VC FC,VS,TIME,YRANGE=100,500
```

Figure 55 EASY Analysis File for HVDC System with Solid Rotor Generator

```
DISPLAY3
A1 F4,VS,TIME,YRANGE=-10,100
V1 F4,VS,TIME,YRANGE=100,400
A2 F4,VS,TIME,YRANGE=-10,100
V2 F4,VS,TIME,YRANGE=100,400
DISPLAY4
ALOS4,VS,TIME,YRANGE=0,60
EO S4,VS,TIME,YRANGE=15,35
EC S4,VS,TIME,YRANGE=-50,50
DISPLAY5
VC L6,VS,TIME,YRANGE=15,45
A1 L6,VS,TIME,YRANGE=0,60
A2 L6,VS,TIME,YRANGE=0,60
SIMULATE
XIC-X
INITIAL TIME=.01
LINEAR ANALYSIS
PARAMETER VALUES
RL L6=.56
AL1FC=60.0
TMAX=.02
SIMULATE
XIC-X
LINEAR ANALYSIS
```

Figure 55 EASY Analysis File For HVDC System With Solid Rotor Generator

(Continued)

/*/*/*/ LINEAR ANALYSIS /*/*/*/

270VDC SOLID ROTOR SYSTEM SIMULATION ***** TEST6A *****

CASE NO. 1 80/09/23. 20.18.49.

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 VO G1	270.00	.100E-03	1
2 ALOG1	40.000	.100E-03	1
3 X3 G1	-.37600E-01	.100E-03	1
4 V2 G1	.27830	.100E-03	1
5 IL FC	40.000	.100E-03	1
6 VC FC	270.00	.100E-03	1
7 A1 F4	40.000	.100E-03	1
8 V1 F4	270.00	.100E-03	1
9 V2 F4	270.00	.100E-03	1
10 A2 F4	40.000	.100E-03	1
11 ALOS4	40.000	.100E-03	1
12 X0 S4	28.000	.100E-03	1
13 X1 S4	255.00	.100E-03	1
14 A1 L6	40.000	.100E-03	1
15 VC L6	28.000	.100E-03	1

RATES AT OP. POINT

1 VO G1 = 0.	2 ALOG1 = .45267E+06	3 X3 G1 = -.16267E-01	4 V2 G1 = 0.
6 VC FC = 0.	7 A1 F4 = -3063.0	8 V1 F4 = 0.	9 V2 F4 = 0.
11 ALOS4 = -.10230E+06	12 X0 S4 = -7860.2	13 X1 S4 = 39738.	14 A1 L6 = -.16727E+06

5 IL FC = -.49567E+07
10 A2 F4 = -6174.8
15 VC L6 = 0.

STABILITY MATRIX NOT SHOWN

15 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-57.1743	0.	57.1743	1.00000
3	-712.983	+- 27298.0	27307.3	.261096E-01
4	-1440.15	+- 2323.75	2733.64	.526787
5	-1630.96	+- 4572.92	4855.07	.335931
6	-3810.95	+- 18380.3	18771.2	.203021
7	-5813.34	0.	5813.34	1.00000
8	-12082.7	+- 20769.1	24028.2	.502865
9	-61934.4	+- .539224E+07	.539260E+07	.114851E-01

Figure 56 Linear Analysis (1) of HVDC System with Solid Rotor Generator

with the new operating point variables. The system stability is apparent as shown in figure 57. The transient responses of selected system variables are shown in figures 58 through 62. All variables appear to be within expected tolerance levels.

Before the second simulation is performed some system loading parameters are increased. The total current through the feeder component is increased to 110 amps with the switching regulator load increasing from 40 amps to 50 amps, and the bus 2 load increasing to 60 amps. An additional 10 milliseconds of time is requested to be simulated with a linear analysis requested at the completion of this simulation. The results of the linear analysis shown in figure 63 show that the system remains stable at this operating point.

The transient response characteristics of the selected variables to the load application are shown in figures 64 through 68. Again, the results are within predictable ranges for this predefined stable system. These models show that when operating with a set of parametric data generated from a stable system, the computer simulated model will operate in the stable region.

/*/*/*/ LINEAR ANALYSIS /*/*/*/

270VDC SOLID ROTOR SYSTEM SIMULATION ***** TEST6A *****

CASE NO. 3 80/09/23. 20.22.29.

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 VO G1	272.20	.100E-03	1
2 ALOG1	38.887	.100E-03	1
3 X3 G1	-.34949E-01	.100E-03	1
4 V2 G1	.25215	.100E-03	1
5 IL FC	37.096	.100E-03	1
6 VC FC	271.53	.100E-03	1
7 A1 F4	39.090	.100E-03	1
8 V1 F4	270.32	.100E-03	1
9 V2 F4	260.63	.100E-03	1
10 A2 F4	39.838	.100E-03	1
11 ALOS4	37.595	.100E-03	1
12 XO S4	31.036	.100E-03	1
13 X1 S4	261.69	.100E-03	1
14 A1 L6	39.491	.100E-03	1
15 VC L6	27.448	.100E-03	1

RATES AT OP. POINT

1 VO G1	= -16763.	2 ALOG1	= -1541.4	3 X3 G1	= .21885	4 V2 G1	= -1.509E
6 VC FC	= 3164.3	7 A1 F4	= 6009.7	8 V1 F4	= -9904.5	9 V2 F4	= .10712E+06
11 ALOS4	= -.11424E+06	12 XO S4	= -14790.	13 X1 S4	= 8491.0	14 A1 L6	= -2066.8
5 IL FC	= 56792.						
10 A2 F4	= 12441.						
15 VC L6	= 1163.7						

STABILITY MATRIX NOT SHOWN

15 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-57.1743	0.	57.1743	1.00000
3	-712.963	+- 27298.0	27307.3	.261096E-01
4	-1440.15	+- 2323.75	2733.64	.526787
5	-1630.96	+- 4572.92	4855.07	.335931
6	-3810.95	+- 18380.3	18771.2	.203021
7	-5813.34	0.	5813.34	1.00000
8	-12082.9	+- 20759.1	24028.2	.502865
9	-61934.4	+- .539224E+07	.539260E+07	.114851E-01

Figure 57 Linear Analysis (2) of HVDC System with Solid Rotor Generator

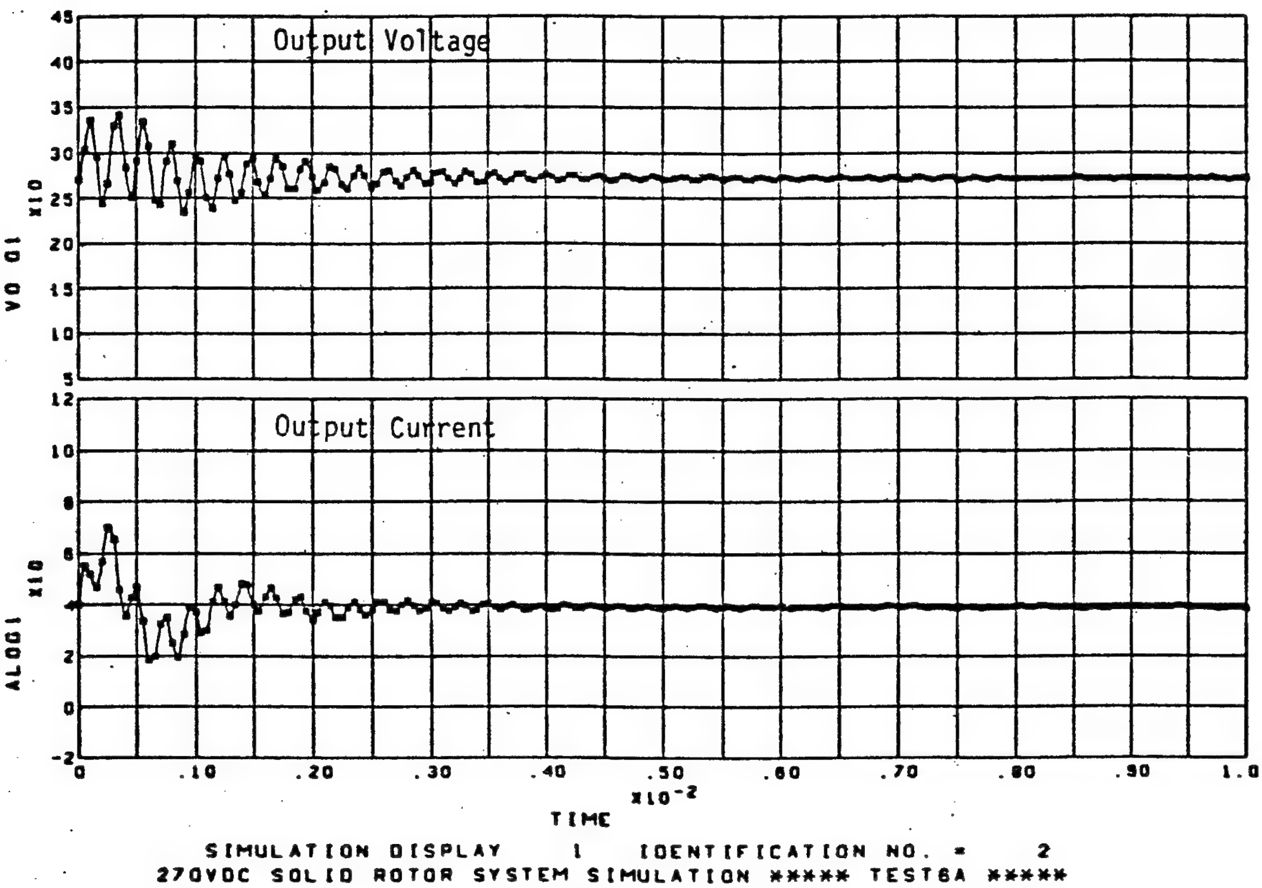


Figure 58 Transient Response (1a) of Solid Rotor Generator

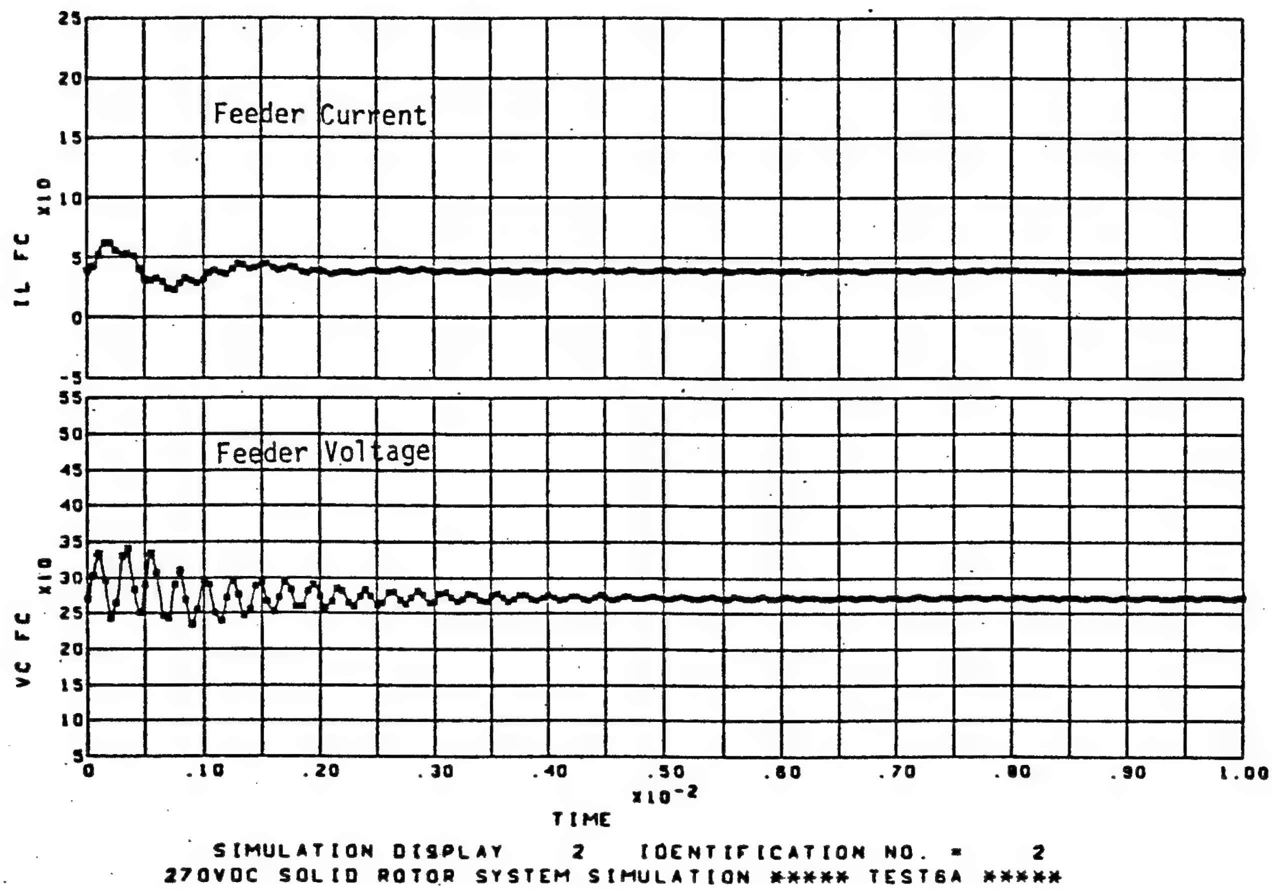


Figure 59 Transient Response (1b) of Flat Conductor Feeder

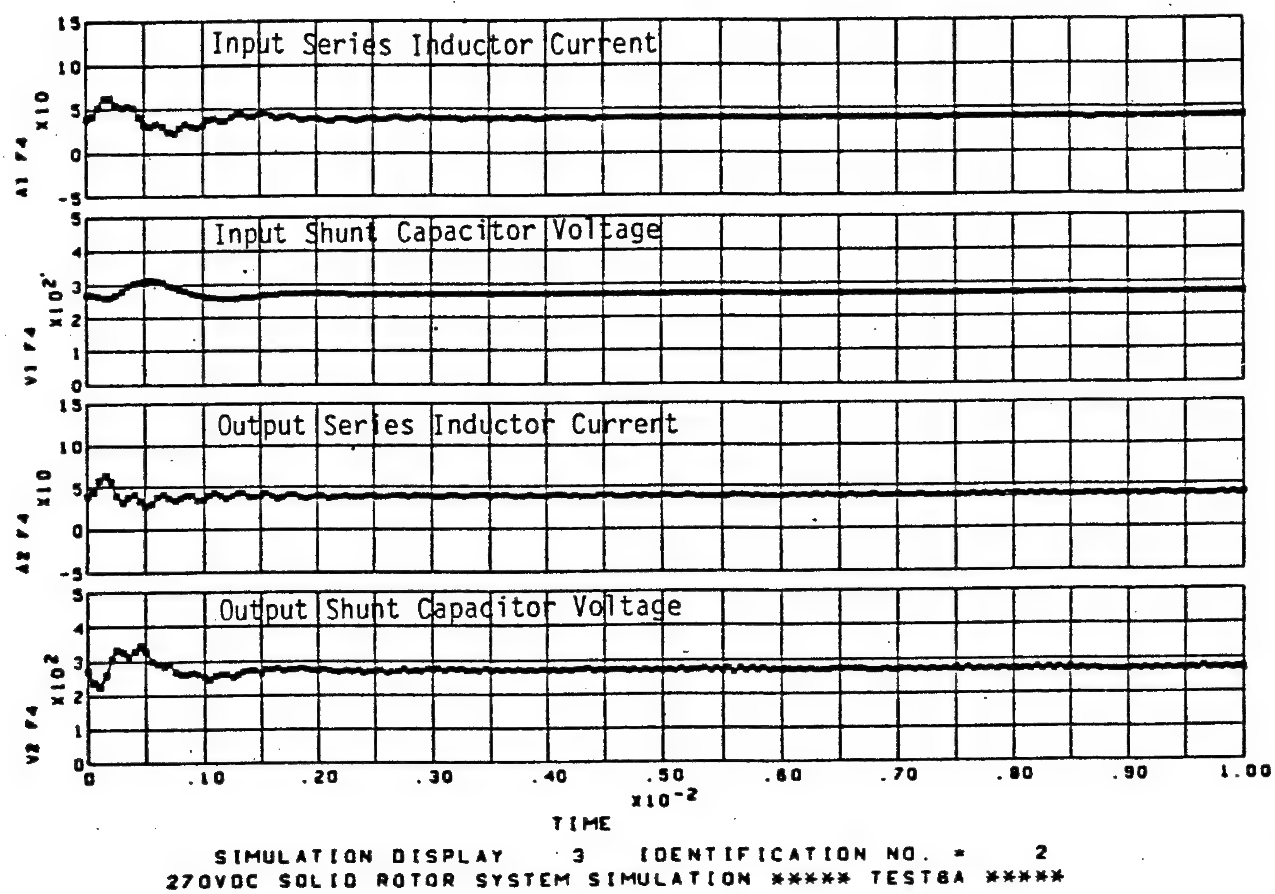


Figure 60 Transient Response (1c) of Switching Regulator EMI Filter

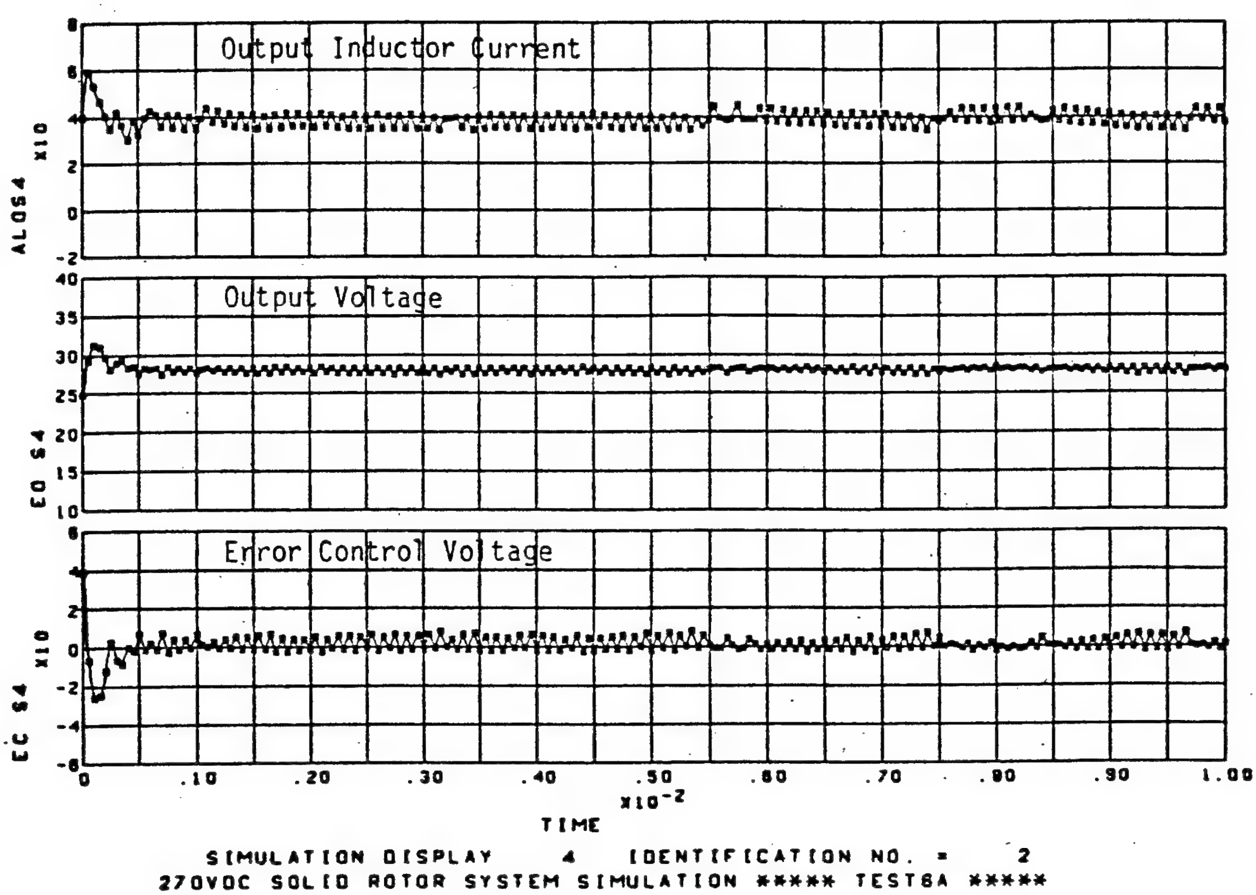


Figure 61 Transient Response (1d) of Switching Regulator

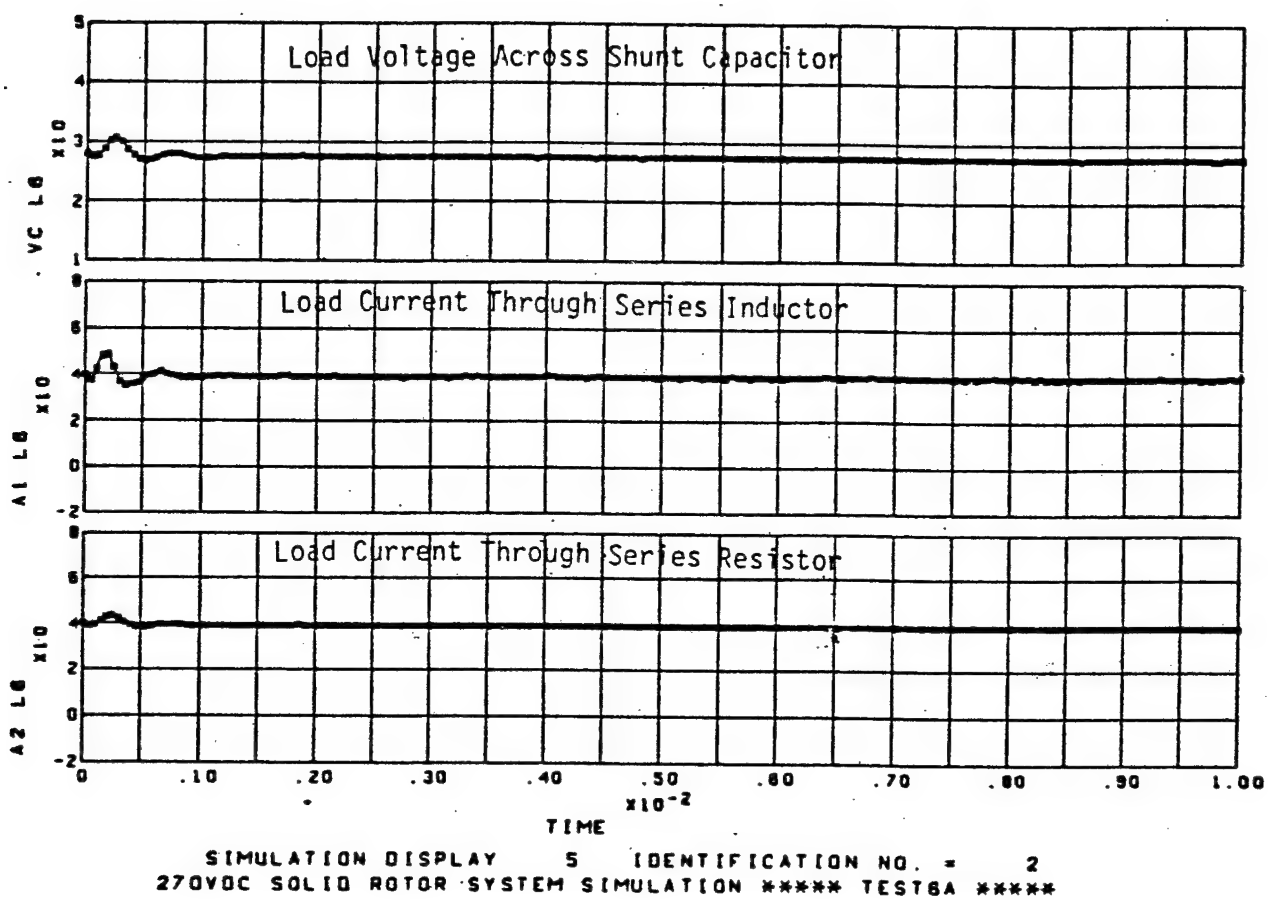


Figure 62 Transient Response (1e) of RLC Load

/*/*/*/ LINEAR ANALYSIS /*/*/*/

270VDC SOLID ROTOR SYSTEM SIMULATION ***** TEST6A *****

CASE NO. 5 80/09/23. 20.27.55.

STATE NAME	OPERATING POINT	PERTURBATION SIZE	INTEGRATION CONTROL
1 VO G1	268.81	.100E-03	1
2 ALOG1	108.85	.100E-03	1
3 X3 G1	-.36332E-01	.100E-03	1
4 V2 G1	.26946	.100E-03	1
5 IL FC	108.63	.100E-03	1
6 VC FC	256.97	.100E-03	1
7 A1 F4	43.676	.100E-03	1
8 V1 F4	265.95	.100E-03	1
9 V2 F4	263.58	.100E-03	1
10 A2 F4	43.709	.100E-03	1
11 ALOS4	43.624	.100E-03	1
12 X0 S4	31.654	.100E-03	1
13 X1 S4	231.66	.100E-03	1
14 A1 L6	46.897	.100E-03	1
15 VC L6	27.300	.100E-03	1

RATES AT OP. POINT

1 VO G1	= 14065.	2 ALOG1	= 1475.0	3 X3 G1	= -.10469	4 V2 G1	= .81221
6 VC FC	= 14674.	7 A1 F4	= -201.24	8 V1 F4	= -429.51	9 V2 F4	= 4720.7
11 ALOS4	= -.11327E+06	12 X0 S4	= -9817.9	13 X1 S4	= 7589.5	14 A1 L6	= 2497.0
5 IL FC	= -161.32						
10 A2 F4	= 14768.						
15 VC L6	= 610.75						

STABILITY MATRIX NOT SHOWN

15 EIGENVALUES

MODE	REAL	IMAGINARY	NATURAL FREQ.	DAMPING RATIO
1	0.	0.	0.	0.
2	-57.1743	0.	57.1743	1.00000
3	-712.963	+- 27298.0	27307.3	.261096E-01
4	-1630.96	+- 4572.92	4855.07	.335931
5	-1786.92	+- 2095.00	2753.57	.648948
6	-4206.22	+- 18253.4	18732.2	.224652
7	-5813.34	0.	5813.34	1.00000
8	-12082.9	+- 20759.1	24028.2	.502865
9	-61934.4	+- .539224E+07	.539260E+07	.114851E-01

Figure 63 Linear Analysis (3) of HVDC System with Solid Rotor Generator

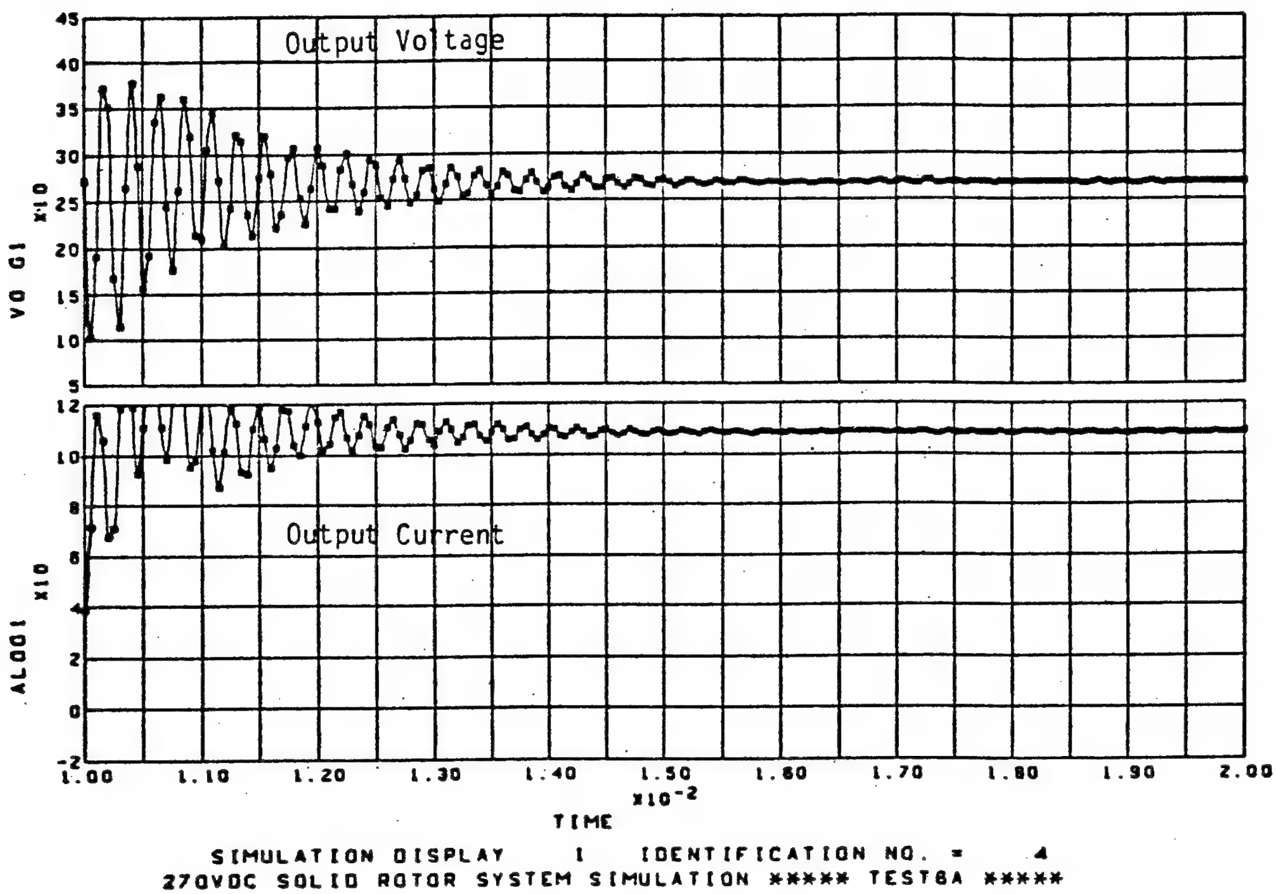


Figure 64 Transient Response (2a) of Solid Rotor Generator

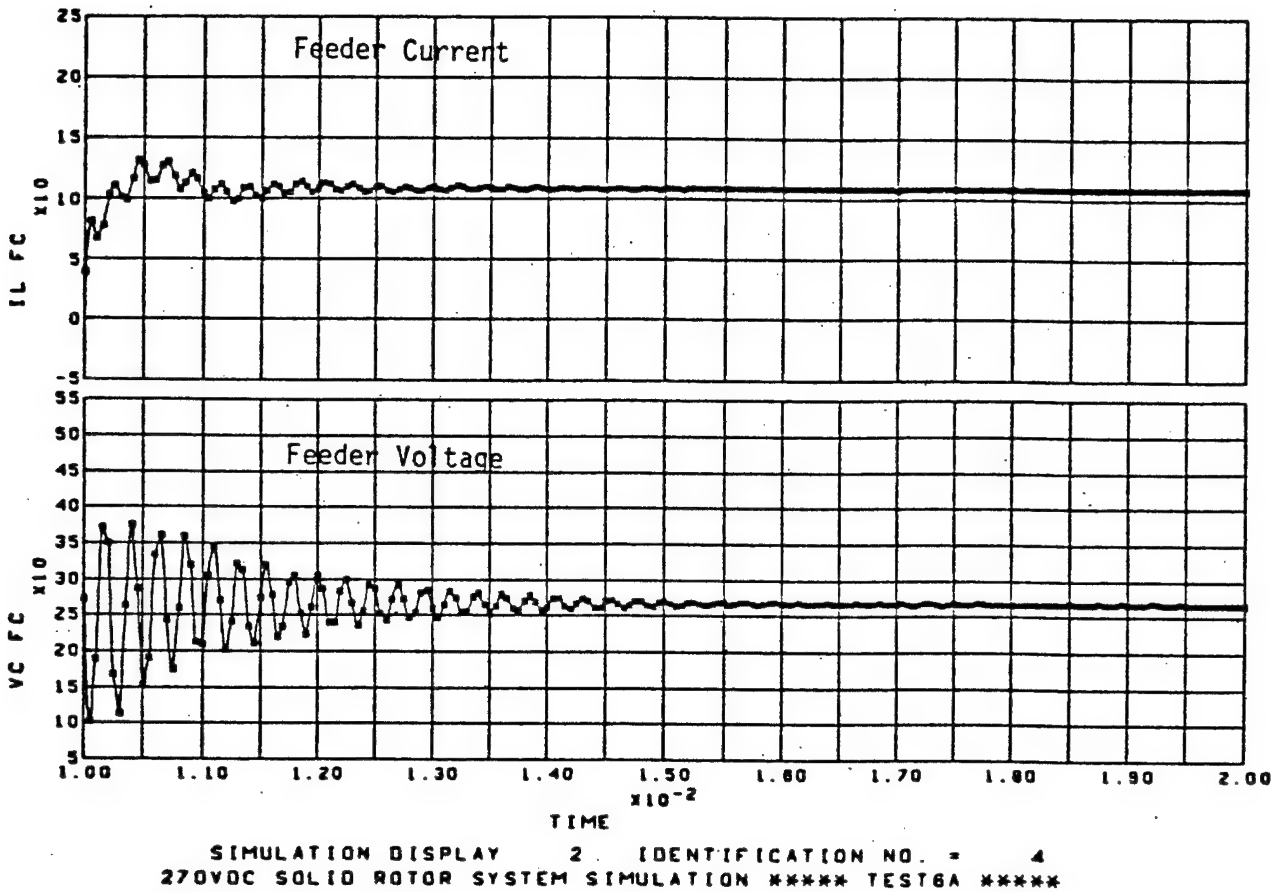


Figure 65 Tranisent Response (2b) of Flat Conductor Feeder

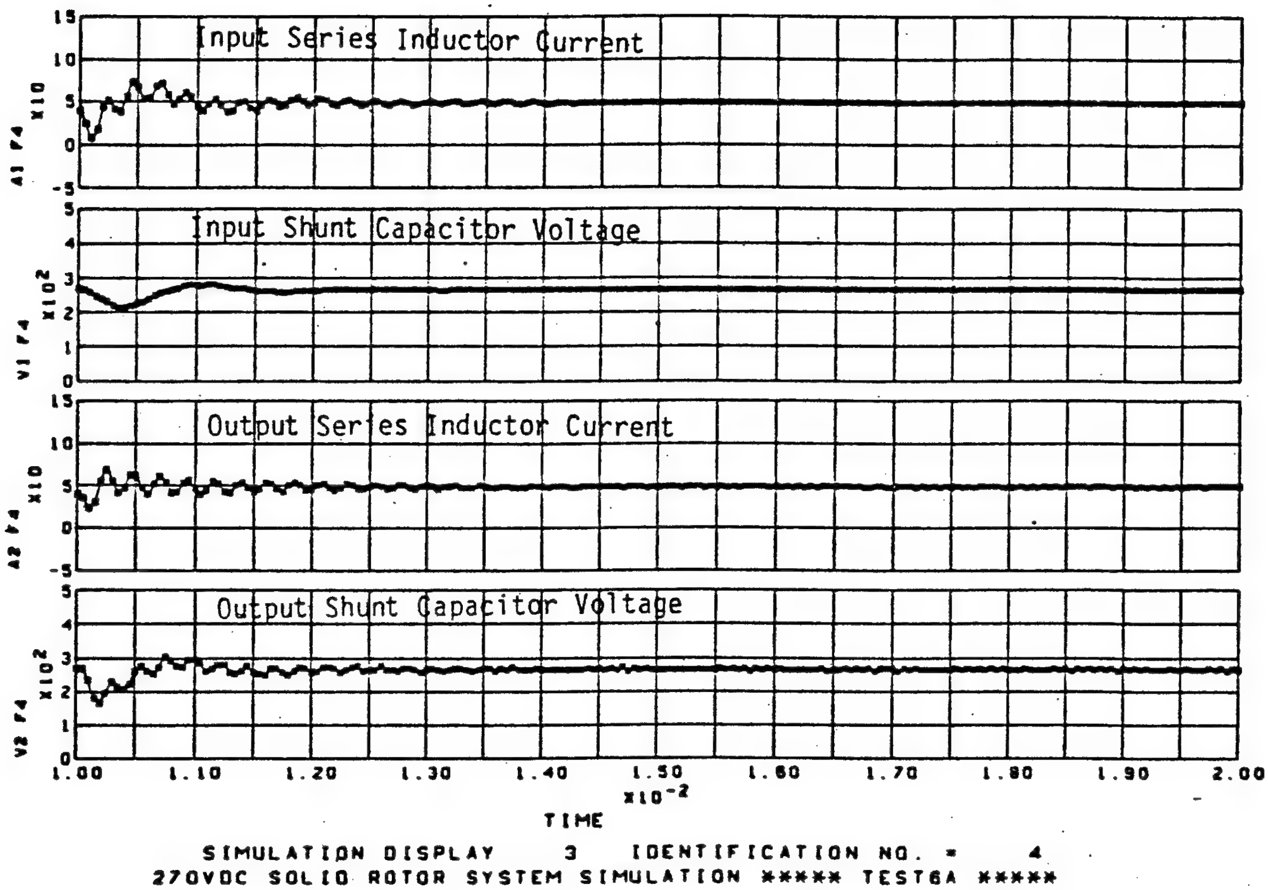


Figure 66 Transient Response (2c) of Switching Regulator EMI Filter

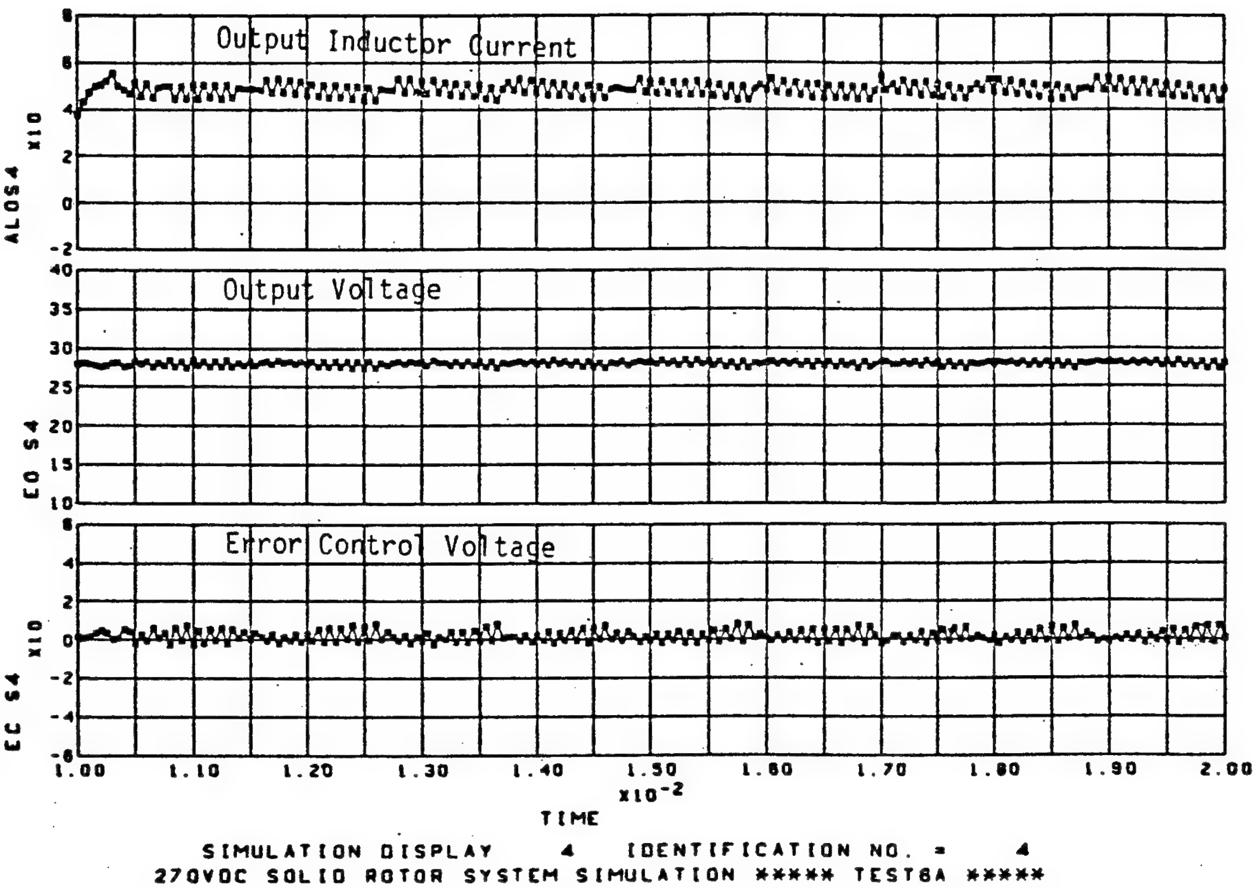


Figure 67 Transient Response (2d) of Switching Regulator

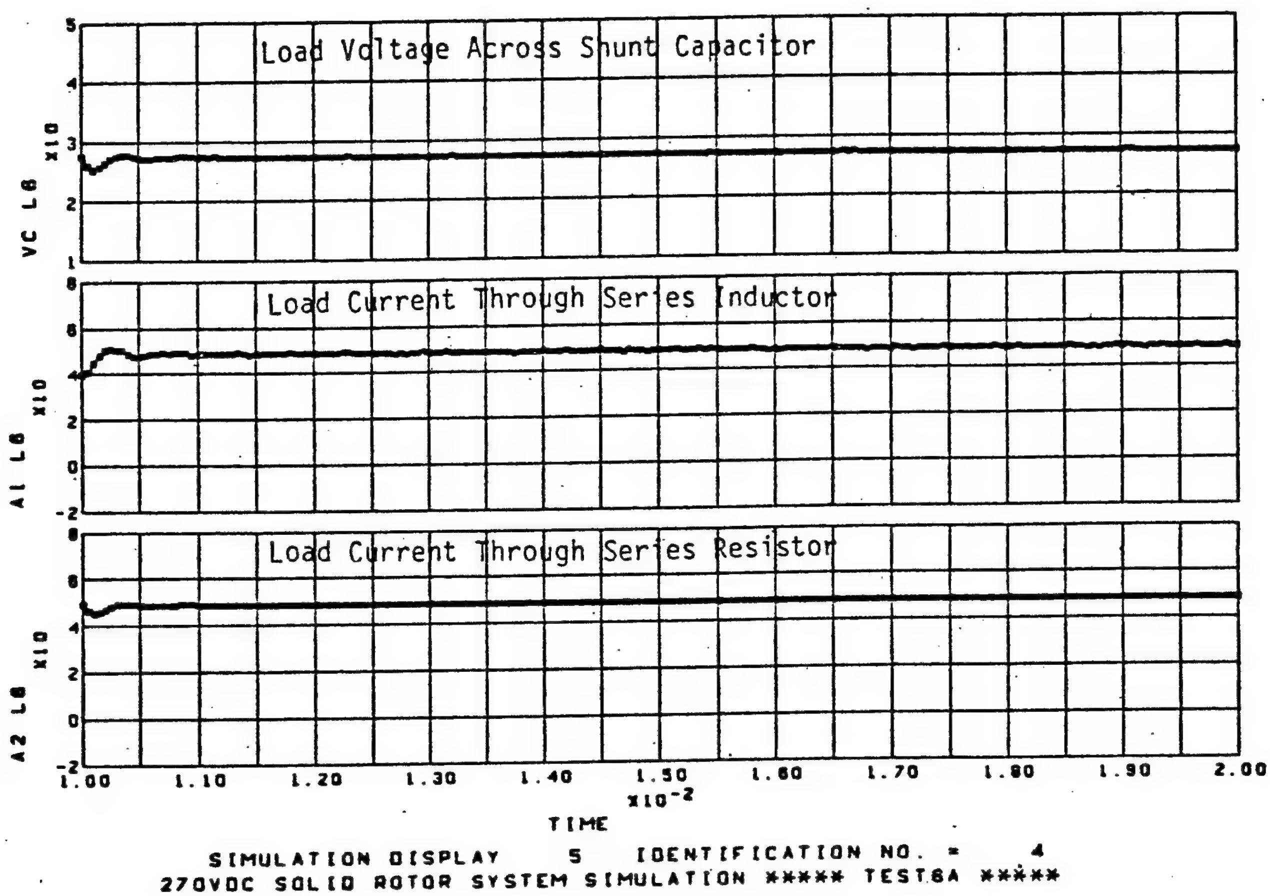


Figure 68 Transient Response (2e) of RLC Load

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The system models were simulated in four configurations. These provided a good test for the component models to correlate simulation results with known physical hardware responses. The hardware response data, however, has been limited mostly to static parametric information. In previous analyses, as detailed in the references refered to in the description of each component, the static models were shown to be stable. The dynamic simulations conducted on the system models using the EASY computer program also showed the components as well as the overall systems to be stable. The models, therefore, correlate with existing hardware from a stability point of view within the limits of the data available.

Although the components developed thus far represent the basic HVDC system elements, other components may be necessary to provide additional information to analyze specific systems. It may also be desirable to increase the complexity of, or simply change existing components as the state-of-the art advances.

Further, to ensure the validity of the components, in particular the wound rotor and solid rotor generator/regulator models, there must be effort expended in the comparison of hardware operating results with computer simulation results. Some of the hardware which can provide the operating data will be available in the months ahead. Test procedures will need to be developed to provide the data necessary to verify the validity of the computer models and to define changes in the models to ensure proper correlation of results.

REFERENCES

1. High Voltage DC Stability Analysis Models, Boeing Document, D180-26020-1, September 28, 1980.

2. EASY User's Manual, BCS Document 10208-127, April 1980.

3. Modelling and Analysis of Power Processing Systems (MAPPS), Final Report, NASA Document DR-1235173.

4. Time Domain Modelling and Stability Analysis of an Integral Pulse Frequency Modulated DC-TO-DC Power Converter, P. P. Iwens, Y. Yu, J. E. Triner, PESC 1975.

5. Discrete Time Domain Modelling and Analysis of DC-DC Converters with Continuous and Discontinuous Inductor Current, R. P. Iwens, F. C. Lee, J. E. Triner, NAS3-18918, August 1977.

6. Generalized Computer-Aided Discrete Time Domain Modelling and Analysis of DC-DC Converters, PESC 1977.

7. Modelling of Switching Regulator Power Stages With and Without Zero-Inductor-Current Dwell Time, F. C. Lee, Y. Yu, J. E. Triner, PESC 1976.

8. Modelling, Analysis and Design of Switching Converters, NASA Document CR-135174, January 1978.

9. Modelling and Measurement of DC-TO-DC Switching Converters and Regulators, R. D. Middlebrook and Dr. S. Cuk, PESC, June 18, 1979.

10. Development of a Standardized Control Model for DC-TO-DC Converters (NASA CR-135072), Y. Yu, R. I. Iwens, F. C. Lee, L. Y. Inouye, August 30, 1977.

11. Switching-Mode Power Supply Technology, J. Foutz, December 1978, Symposium for a Rational Approach to Powering Shipboard Electronics.

12. Watch Out for Problems (EMI Filters), N. O. Sokal, Electronic Design, January 4, 1974.

13. An Adaptive-Control Switching Buck Regulator-Implementation, Analysis and Design, F. C. Lee, Y. Yu, IEEE, PESC 1979.

14. Input Filter Design for Switching Regulators, F. C. Lee, Y. Yu, IEEE, PESC 1979.

15. Digital Simulation of a Three-Phase Generator, P. J. Leong, I. S. Mehdi, NAECON 1978.

16. Dynamic Analysis of Power Systems, Boeing Document D2-6766, October 11, 1960.

17. DC Wound Rotor/Voltage Regulator Control Loop Analysis, Lear Siegler, October 28, 1978.

18. 270 VDC Generator System Development, AiResearch Document, June 1980.

19. Flat Cable for Power Distribution, J. D. Segrest, Task #F61512001.

20. Flat Conductor Cable Application Study for Airplane Power Feeders, J. P. Morris, Boeing, June 6, 1968.

EASY PROGRAM SUMMARY

APPENDIX A

APPENDIX A

EASY PROGRAM SUMMARY

INTRODUCTION

This appendix briefly outlines the EASY program and provides some information on the use of EASY. A detailed presentation of the EASY program and its application to Electrical System Analysis can be found in reference 1 and 2.

The EASY system provides a modular approach to both dynamic system model building and analyses. EASY was built not as a programming language but as a means for assembling complex models from modelling modules. Predefined modules, referred to as components, may be stored in libraries or they may be defined as part of a model description. The modelling components serve as system analysis building blocks. They may have several input and output ports and, at each port, information may flow either into or out of the block. For predefined components, the EASY user need only be concerned with the interconnections between components. All detailed connections of signal paths between blocks are accomplished automatically by the EASY program with a minimum of user intervention.

As shown in figure A-1, the EASY system consists of two programs, a Model Generation program and an Analysis program, and a library of predefined Standard Components. The EASY Model Generation program allows mathematical models of nonlinear dynamic systems to be constructed easily. Many of the routine programming tasks that are required to construct such a model are performed by the Model Generation program. A schematic diagram of the system being modelled and numerous other aids to the model building process are provided automatically by the Model Generation program.

Predefined Standard Components model many of the common effects found in dynamic systems. Standard Component libraries have been developed for a variety of applications such as: vehicle dynamics, environmental system dynamics, wind energy systems, power plant dynamics, etc.

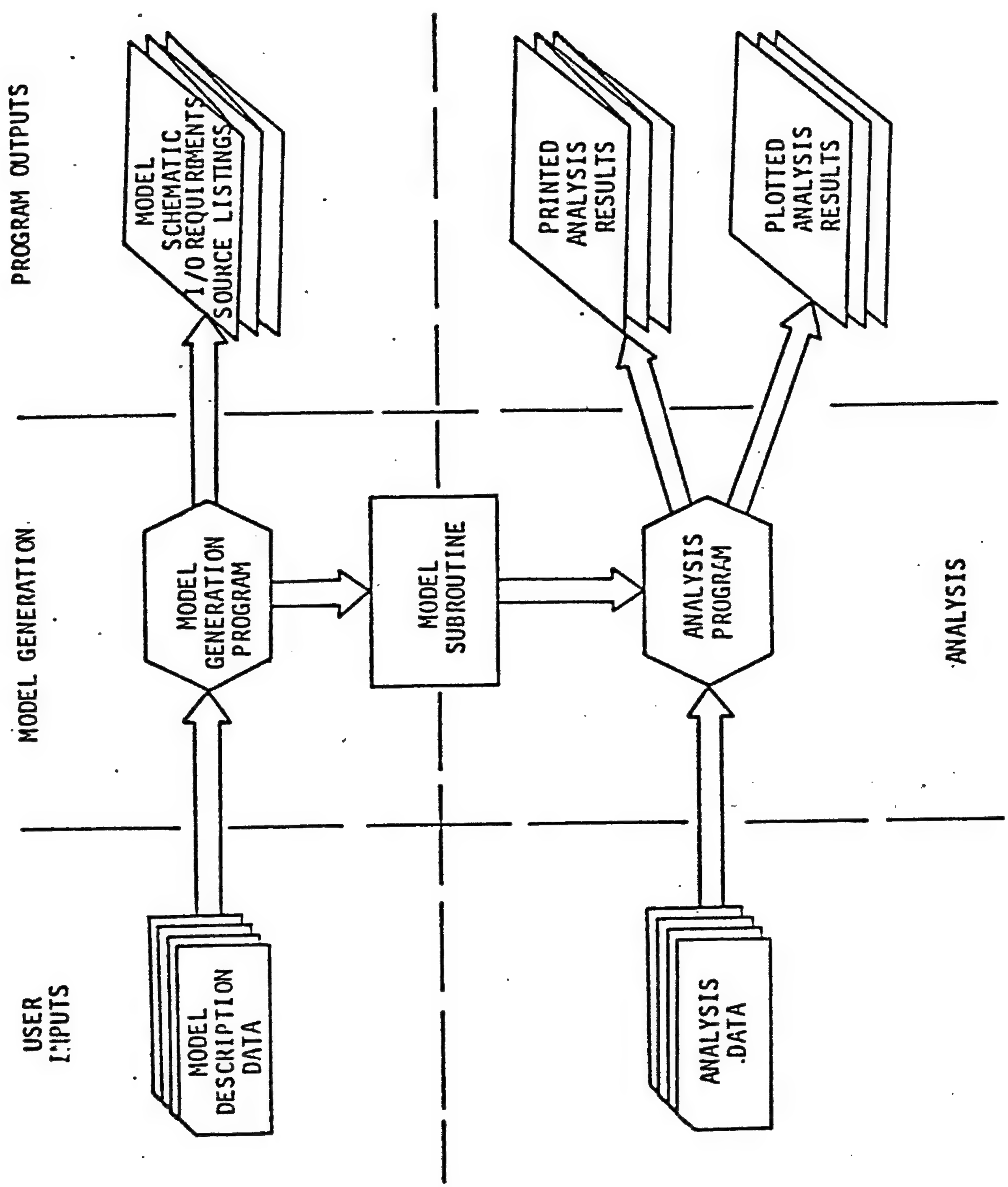


Figure A-1 EASY Program Organization

If portions of a dynamic system cannot be modelled conveniently with available Standard Components, additional components can be created in Fortran by the user. User-created components can replace Standard Components and can be stored on a user's permanent file. An EASY user can thus build a collection of modelling components tailored to his technical area.

Once a model has been constructed for a nonlinear dynamic system, the EASY Analysis program allows various dynamic nonlinear and linear analyses to be applied to that model. The following analysis techniques are available:

- Time history generation, i.e., nonlinear simulation
- Linear model generation with eigenvalue and eigenvector calculations
- Frequency response analysis
- Root locus calculation
- Steady state analysis
- Stability margin calculations
- Optimal controller synthesis

The ability to easily bring various analytic methods to bear on a nonlinear system without having to manually generate linear models can greatly reduce the time required to solve difficult dynamic system analysis or design problems. By having several analytic tools in addition to simulation, considerable savings in computer costs can be achieved. This is possible since many of the linear techniques available with EASY use a fraction of the computer time required to obtain system information by nonlinear simulation. Examples are stability margins as obtained by linear methods rather than simulation, and selection of control system gain and compensation parameters via root locus techniques, rather than numerous simulation runs. The EASY program is written for the CDC computer. Figure A-1 shows the general organization of the program.

The EASY program was originally developed under an Air Force contract to provide methods for modelling and analyzing aircraft environmental control systems. In 1976, a second Air Force contract extended the application of the program to include aircraft flight dynamics. Since October 1976, a

Boeing-funded research and development effort has been undertaken to modify the program for use on a wide variety of control system analyses. The program now includes component models for many types of vehicles and control components, matrix and vector notation at all program levels, capability to model and analyze continuous and discrete systems, larger modelling capacity allowing large scale simulations, ability to store time history data on magnetic tape, and more user oriented Fortran statements.

MODEL GENERATION

The EASY Model Generation Program uses a block diagram type of approach for constructing the different system models. It is based upon the assumption that the system analyst will construct a detailed schematic block diagram of the system to be analyzed. The blocks of this schematic will be modelled by one or more EASY components. Three types of EASY modelling components can be used:

1. Predefined Standard Components
2. User-defined Fortran Components
3. User-defined Macro Components

Standard EASY components include electrical system models, aircraft, missiles and spacecraft modelling components, wind models, statistical analysis, flexible model and orbital components, and multi-purpose control system components. The parts of a system which cannot be modelled using these standard components are included by appropriate user-furnished Macro or Fortran components in the system description.

All interconnections between the different standard components and to the FORTRAN blocks are accomplished by the Model Generation Program. The analyst draws the block diagram by specifying the location of each standard component in the schematic diagram and all of the components that provide inputs to that component. The Model Generation Program then generates name labels and the

proper interconnections between the specified components. This is accomplished by matching the input quantities required by each component to the output quantities of the components specified as providing inputs.

After processing the complete system model description, the Model Generation Program generates the schematic diagram of the model showing all of the interconnections between the components in a manner similar to the analyst's original diagram. It shows the quantities such as voltages, currents, etc., that are used to form each interconnection. This schematic is produced on the lineprinter and provides a rapid graphic check on the program's interpretation of the model description.

In addition, the program produces a complete list of the input data that will be required by each component to complete the model description. The scalar and vector parameters and tabular data required for the analysis are included in this list. The program assumes that any quantity not supplied by another component will be supplied as a fixed parameter by the analyst. Thus, requests for nonparameter items in the input data list reveal any connections that have been omitted from the system model description.

DYNAMIC ANALYSIS OF CONTINUOUS OR DISCRETE SYSTEMS

The EASY Analysis Program allows several different, dynamic, static, linear, or nonlinear analysis techniques to be used on the dynamic system model generated by the Model Generation Program. In addition to normal analysis techniques, optimal linear controllers based on Kalman optimal linear regulator and Kalman filter theory can be synthesized by the program. The performance of such optimal controllers when operating with the nonlinear system can be analyzed using any of the analysis techniques.

Both continuous systems, i.e., those described by ordinary nonlinear differential equations, and discrete systems, can be modelled and analyzed by the EASY program. The analysis techniques automatically switch to discrete methods if one of the discrete components, DE, DF, DL, DT, DZ, or SH is included in the system model (reference 2). All data input, output, and analysis commands are the same for both continuous and discrete systems. The

only restriction for discrete systems is that the total number of sampling periods is restricted to 10. This refers to the sampling period parameters, TAU, for each discrete component. The name of these parameters must always start with the letters TAU, and no other parameter may start with the letters TAU.

A description of the analysis techniques available through the EASY Analysis Program follows.

1. Steady State

A Newton-Raphson equation solver is applied to the nonlinear algebraic equation set. The program will calculate either a single steady state condition, or will calculate the steady state of the system model as a function of some system parameter or operating point.

2. Linear Analysis

A linear representation of the system, referred to as the system stability matrix, is determined at any specified operating point. The stability matrix contains the partial derivative of each state time derivative with respect to each state. These partial derivatives are calculated twice using different perturbations, enabling the analyst to determine the degree of nonlinearity of the system and a measure of the validity of the linear model. Severe nonlinearity indicated by this approach may be inherent in a model, but more often is a result of a coding error which can readily be detected and corrected.

In addition to the stability matrix, the system eigenvalues are calculated and expressed in the complex form. The corresponding natural frequency and damping ratio of each real eigenvalue or complex conjugate pair of eigenvalues are also given. Since system instability is indicated by a non-negative real eigenvalue, the stability of a system can be evaluated quickly at any operating point. By utilizing the capability of the EASY program to "freeze" one or more states, the cause of instabilities can usually be easily determined.

3. Stability Margins

An important task in dynamic system analysis is to determine the range of values that certain system parameters can assume without causing system instabilities. Even using the linear analysis described above, it can be a tedious task to locate the stability limits on several system parameters. The EASY analysis program contains an efficient method for locating upper and lower stability limits and the frequencies at which the system will oscillate if these bounds are violated. This feature of the program allows the stability margins of up to ten system parameters to be evaluated in a single analysis. The gain margin, namely the ratio between the value of a parameter which causes the system to go unstable and the actual value of the parameter, is determined.

4. Transfer Functions

One of the most common methods of linear system analysis is the examination of the transfer function or frequency response operator between two points in a dynamic system model.

The EASY analysis program provides the capability to quickly evaluate the transfer function between any two points in the system model which have been identified as parameters, variables, state variables, or state variable derivatives. This capability can be combined with ability to select various operating points and to "freeze" out selected degrees of freedom of the model. It is thus possible to examine the frequency response of individual components within the system or the total system response. The results of such studies can often be used to correlate the dynamic model results with laboratory or field tests of the actual system. Transfer function results can be requested in the form of Bode, Nichols or Nyquist plots.

5. Root Locus

A root locus analysis provides a graphic display of the system's dynamic behavior as a function of some system parameter. For nonlinear systems, the dynamic behavior also varies as a function of the operating point of the system. The EASY analysis program has extended the root locus analysis, so that it may be performed as a function of any operating point value, as well as any system parameter.

6. Eigenvalue Sensitivity

The root locus analysis provides a great deal of information as to the effect of single parameter on a system's dynamic behavior. However, it is often desirable to know the sensitivity of system stability to many different parameters. The eigenvalue sensitivity analysis provides this type of information. For a given parameter, it displays how that parameter affects each eigenvalue of the sytem. A measure of sensitivity is calculated for both the real and imaginary part of each eigenvalue. The magnitude of this measure reveals if the specified parameter affects a particular eigenvalue, while the sign of the measure tells if a positive increase in the parameter is stabilizing or destabilizing to that eigenvalue.

7. Function Scan

A general function scanning capability is provided by the EASY analysis program. This capability allows the numerous algebraic functional relationships that exist in a dynamic system model to be presented in graphic form. The dependent variable of such functions can be: (1) any state variable, (2) state variable derivative, (3) or variable defined in the system model. The independent variable of such functions can be any of the above, or any model parameter. These general functions are evaluated under static conditions, i.e., no integration occurs. They can be evaluated at any operating point chosen by the system analyst. The functions scanned can have either one or two independent variables.

8. Simulation

For nonlinear simulation, EASY contains a choice of integrators. The default is a variable order Gear integrator which has been found to be very efficient in simulating the "stiff" systems (i.e., systems with widely spread eigenvalues) found in electrical system modelling. During nonlinear simulation, the flow of information between the dynamic models of the system and the integrator package is illustrated in figure A-2. In essence, derivatives of the state variables are calculated within the component models and are fed to the integrator. Updated values of the states are then returned to the models, and the process repeated for the next time step. This modular arrangement, with the integrator package totally separate from the models, means that additional integrators can be added to EASY without difficulty. Presently, the following integrators are available:

1	DIFSUB:	Original Gear integrator with variable step and variable order.
2	NRKVS:	The fourth order Runge-Kutta variable step integrator
3	HEUNS:	Fixed step explicit method of order two.
4	EULER:	Fixed step explicit method of order one.
5	ADAMS:	Automatic step-size/order selection methods using Adams-Bashforth predictor/Adams-Moulton corrector pairs of orders 2 through 12.
6	STIFF GEAR:	The backward differentiation (stiffly stable) variable order variable step size.

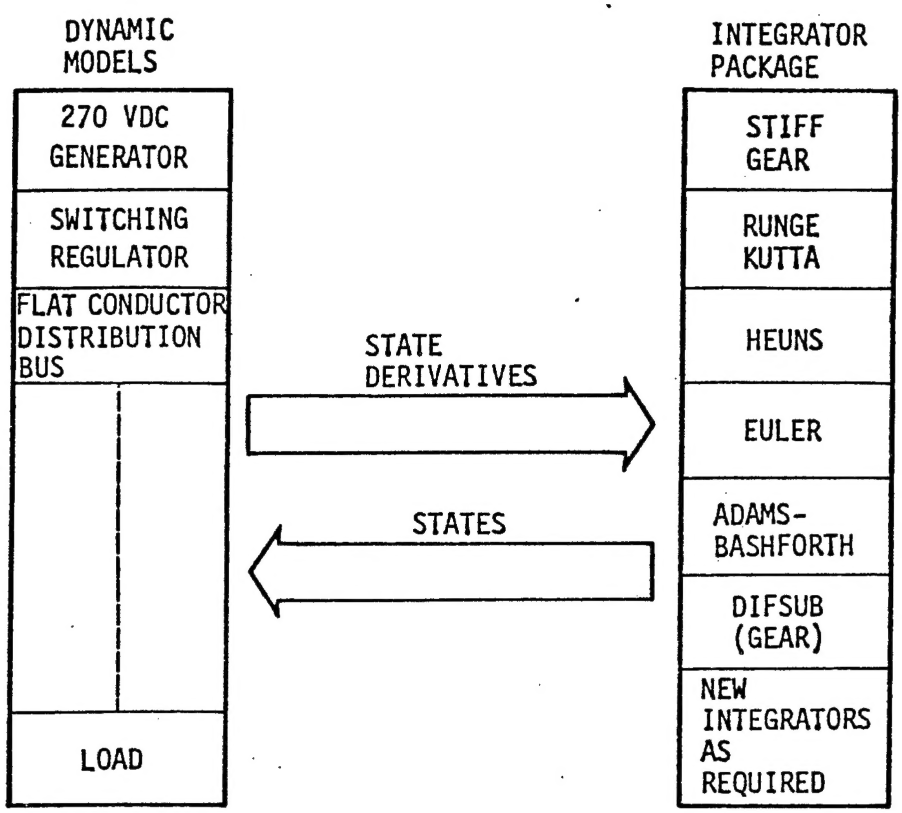


Figure A-2 Information Flow Between Dynamic Models and Integrator Package of the EASY Program